Integrated ICT-platform based Distributed Control in electricity grids with a large share of Distributed Energy Resources and Renewable Energy Sources

Evaluation of the Results and Guidelines for EU Research

Deliverable D8.2

Identifier:	INTEGRAL_D8.2
Date:	05-04-2011
Class:	Deliverable
Responsible Partners:	NTUA/ICCS, ECN, IDEA, BTH, KEMA, INPG, HUMIQ, CRIC, Wattpic
Annexes:	
Distribution:	PU
Overview:	The evaluation of the Results and Guidelines for EU Research are presented

<ins>The INTEGRAL consortium consists of:</ins>

ECN	Principal Contractor & Coordinator	The Netherlands
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INPGrenoble	Principal Contractor	France
HUMIQ	Principal Contractor	The Netherlands
CRIC	Principal Contractor	Spain

Control Versions:

Version	Date	Author	Description of Changes
D8.2 0_1	1/5/2010	Aris Dimeas	First Draft
D8.2 0_2	7/6/2010	Rene Kamphuis	Input for Demo A
D8.2 0_3	15/02/2011	Evangelos Karfopoulos	Input for Demo B
D8.2 0_4	15/02/2011	Raphael Caire	Input for Demo C
D8.2 0_5	29/03/2011	Aris Dimeas	Pre Final Version
Final	05/04/2011	Raphael Caire	New Inputs for Demo C

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References

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Acronyms and Abbreviations

ADD	Architectural Design Description
AMR	Automatic Meter Reading
ADSL	Asymmetric Digital Subscriber Line, data communication over phone line
CSV	Comma Separated Value, a common format for exchanging data
DSO	Distribution System Operator
PM	PowerMatcher
PLC	Programmable Logic Controller
CHP	Combined Heat and Power generation
CRISP	distributed intelligence in Critical Infrastructures for Sustainable Power
CVPP	Commercial Virtual Power Plant
DG-RES	Distributed Generation with Renewable Energy Sources
DER	Distributed Energy Resources
DG	Distributed Generation
DNO/DSO	Distribution Network/System Operator
DRR	Demand Response Resources
DSM	Demand Side Management
DMS	Distribution Management System
DSP	Digital Signal Processor
EPS	Electric Power System
EV	Electric Vehicle
GSM	Global System for Mobile communications
HV	High Voltage
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technology
IIDC	Integrated ICT platform for Distributed Coordination
ISO	Independent System Operator (~ TSO, USA context); International Standards Organization
JADE	Java Agent Development Environment
LAN	Local Area Network
LV	Low Voltage
MAS	Multi-Agent System
MG	Microgrid
MGCC	Microgrid Central Controller

MTBF	Mean Time Between Failure
MV	Medium Voltage
PM	Power Matcher
PRP	Programme Responsible Party
PV	Photo-Voltaic
RES	Renewable Energy Sources
SOC	State-Of-Charge
SOA	Service Oriented Architecture

Executive Summary

The purpose of the Integral project is to test different ICT infrastructures in different scenarios. For this purpose, three different demos are developed: Demo A, B and C. These ones are detailed as previous study in the different D2.x and D4.x deliverables.
Scope of this deliverable is to present the results of the evaluation procedure of the Demo Sites as described in D8.1. The evaluation considers the results of the WP5, WP6, WP7, WP9 and proposes guidelines for future research.

1. Introduction

Scope of this deliverable is to present the public results evaluation procedure of the Demo Sites. Since the core of the project is the design of an integral architecture, the target is not only to evaluate performance, but also to enrich knowledge from an application point of view by exchanging the experience gained in the different installations. This evaluation aims to prove whether the three control algorithms can be incorporated into one single system.

This deliverable is outlined as follows: In Chapters 2 to 4 the Demos A,B and C are presented accordingly. In the last Chapter the evaluation procedure of the overall architecture is presented.

2. System operation and economic evaluation for demo A

2.1 Introduction

The requirements, architecture and configuration of the test environment for demo A have been extensively described in other deliverables (see D2.1, D4.1, D4.4 and D5.1). For the test configuration a global measurement strategy and planning has been described in D8.1. The report D5.3 refines this strategy in a detailed test-plan.

For field-test A, a number of use cases (applications) have been defined (see D5.1a of this project for detailed use case descriptions). D8.1 also states the parameters measured and stored in the database. Data pertain to electrical parameters, buffer levels, temperatures, market information and internal evaluation parameters around operation of the coordination mechanism. Parallel to the current work, a separate project has been started for Essent, a Dutch energy company, to use the infrastructure also for real-time market operation for trade dispatch of the Integral VPP-cluster. This has led to extension of the normal operation use case.

In the following use case key validation indicator descriptions, the evaluation procedures will be based on five levels:

- Proper **system operation** and Device **validation**. During normal operation of the use cases, the operation of the cluster has to be checked for proper configuration and compliance to expected behaviour. For thermal comfort devices, this would mean monitoring power profiles, temperatures and buffer level profiles as a function of the time-of-day for all installations.
- **PowerMatching operation** validation. The shape and steepness of the individual and aggregated bid-curve and the effects on it on a per use case basis is inspected. Other validation comes from verifying and analyzing the real-time internal price development as function of time-of-day over a prolonged period within the use case context.
- **Grid component validation**. Judging the behaviour of a part of the power matcher cluster in grid operation and from an asset planning point of view. The tool in this respect is the load/generation duration curve. In utility operations these are used to right-size components in the grid. Within the use case contexts, checking the degree of flattening of the DSO Concentrator Agent and HomeMatcher Concentrator agent load distribution curves in the coordinated and non-coordinated cases will provide the required information. The DSO concentrator agent performs the dual goal optimisation for the commercial optimization and the HomeMatcher concentrator agent the optimization goal for coupling demand and supply behind-the-meter.
- **Demand response/generation flexibility potential**. Key figure in this respect is the number of kW shiftable per time unit measured individually or in the cluster. The time unit in the latter depend on the operation of the device for the individual use case.
- **Stakeholder cost evaluation**. In the use cases, metering data are collected at the level of individual devices, in an aggregated manner per household or for the total cluster. For the commercial operator as a stakeholder the value of the cluster will depend on the current external market situation. For an end-user, compared to traditional one or two-zone tariffs, some innovative pricing schemes are also defined. These attribute profit to active end-users, that allow flexibility margins to the operation of the devices. Also, for the micro-CHP customers, the gas bill will increase and the electricity bill will decrease and, for the heat pump customers the electricity bill will increase but the gas bill will decrease. Grossly, the cost however have to go down.

In the following sections, the way the indicator types are determined per use case is further detailed.

2.2 Key performance indicator figures per use case

2.2.1 Cost-effective use of energy.

The Prosumer[1] operates a household with electricity generators and electricity consumers. The Prosumer tries to use these devices as cost effectively as possible. ‘Cost effective’ in this context means maximising economic benefit from time-dependent tariff differentiation. The implementation in terms of the Power Matcher is by introducing an adaptation of the aggregated bid-curve at the home concentrator level. This set-up favours local bids and discourages imports and exports. The incentive for bid-curve construction comes from the (possibly –artificial-) tariff scheme offered to the user. In the scheme the main incentive will be the avoidance of distribution and transport tariffs by using self-produced electricity. Scope of the analysis will be the confined ECN D-dwelling configuration and the Hoogkerk comfort device cluster.

System operation and **Device validation**	The bid and device hydraulics control logics (e.g. filling of the heat buffers at adequate times) are checked.
PowerMatching operation	Power matching validation takes place by inspecting the average gradient of the bid-curves in the concentrated and non-concentrated case.
Grid component validation	Total load duration curves will be constructed; the increase of the degree of flattening will be determined by the Home Concentrator bid-transformations.
Demand response/generation flexibility potential	Flexibility potential evaluation takes place by determining the price elasticity, i.e. how much demand/generation response is possible without impairing the comfort limits.
Stakeholder cost evaluation	As a End-user level key figure, the expected lowering of the centrally metered value is determined and checked for the maximal achievable value.

2.2.2 Reduce residential area peak load

In this use case, applying active demand response and generation management of shiftable resources combined with operation of a Distribution agent in a PowerMatcher context for the residential sub-cluster should lead to lowering peaks at the transformer level in the distribution system. Demand response for capacity related applications are discussed extensively in D4.4 of this project. Peak loads may occur due to the simultaneous operation of the demand (heat-pumps on cold winter days) and the supply (must-run PV in summer or micro-CHP in winter). In the DSO-Agent use case, the coordination level is laid one level up as compared to the Home aggregator, discussed earlier.

[1] Prosumer is a contraction of consumer and producer; it refers to a utility customer, that apart from consumer devices also has production devices like PV, fuel cells

System operation and **Device validation**	The load is constructed from the summed power realisations from the home meters. Summing the realized Power readings for the cluster is checked
PowerMatching operation	Here, the first validation level is on the level of the aggregated bid-curve, collected by the DSO-Agent. Depending on this measured 'load' of the transformer, the DSO-agent imposes a transformation of the bid-curve.
Grid component validation	Total load duration curves will be constructed; the increase of the degree of flattening will be determined by the Home Concentrator bid-transformations.
Demand response/generation flexibility potential	The maximal bandwidth in kW of load reductions is determined, which flexible load/flexible generation devices may offer without impairing end-user comfort levels.
Stakeholder cost evaluation	The cost of the amount of power not-served or not generated at a particular moment in time is determined and the end-user tariff adjustment to compensate is.

2.2.3 Commercial imbalance reduction

This use case involves all sub-clusters combined in a portfolio operating in a market context. The market context, in this case, consists of following in real-time predefined time-depend portfolio program of net demand and supply issued on the basis of planning of the connected resources. A real-time connection to markets is envisioned also including the full-electric vehicle fleet operation.

System operation and **Device validation**	The total portfolio realisation is checked. A real-time connection to markets is monitored also including the full-electric vehicle fleet operation and a trade dispatch agent. The time-dependent margin between forecast and realisation will be determined. Nine different portfolio pricing models will be used.
PowerMatching operation	The market context, in this case, consists of the real-time predefined time-depend portfolio program of net demand and supply issued on the basis of planning of the connected resources.
Grid component validation	-
Demand response/generation flexibility potential	The flexibility of the total cluster is determined in the form of the total amount of power that can be liberated/consumed as a function of time and of time-of-year. Furthermore, the achievable ramp-up/ramp-down compensation capabilities of the Commercial Virtual Power Plant will be determined.
Stakeholder cost evaluation	The market cost and benefits are determined in view of the pricing models.

2.2.4 Valorisation of renewable electricity

In this use case, the mechanism of pre-emptively lowering pre-production peak consumption, if a forecast of high local production of PV around 12 o'clock in summer with minimal local demand will be shown and, in the same way, lowering flexible generation during the PV-peak; classic example is operation a washing machine automatically on power produced from PV. Forecasts and realisation of solar and wind have to be available in this type of analysis.

System operation and **Device validation**	The must-run devices are checked for their realization and forecast. Proper operation of flexible loads is monitored.
PowerMatching operation	The market context, in this case, consists of fixed generation and flexible loads or vice-versa
Grid component validation	-
Demand response/generation flexibility potential	The flexibility of the cluster is determined in the form of the total amount of power that can be liberated/consumed as a function of time and of time-of-year.
Stakeholder cost evaluation	-

2.2.5 Monitor own household

Currently, in translating system cost (market prices, distribution tariffs etc) to end-users flat or day/night tariffs are used based on a consumption profile categorisation. In this use case, cost reduction effects once a semi-artificial real-time pricing environment is established. By using this mechanism, mapping of system costs can be done in a more optimal way. Analysis of this use case will be done in combination with some behavioural studies of the inhabitants of the homes, where the devices are installed (a separate project Flexines, executed in Groningen, will be coupled to this end). A further description can be found in the following chapter.

3. Evaluation of architecture and infrastructure for Demo A

This chapter describes the results of the evaluation of the system architecture and infrastructure which were created to execute work package 5. The aim of this work package is to demonstrate in a field test distributed control under normal operating conditions [DoW]. As field test 25 households, a lab facility, a wind turbine, electric cars and a demonstration house were connected by means of a smart infrastructure. In the lab facility a demonstration set-ups were constructed including heating systems and smart domestic appliances (freezer and laundry machine). Furthermore a solar panel cluster on the lab facility was included in the field test. Parts of the cluster were virtually attached to the each household.

The PowerMatcher concept was used to control the distributed generation and consumption.

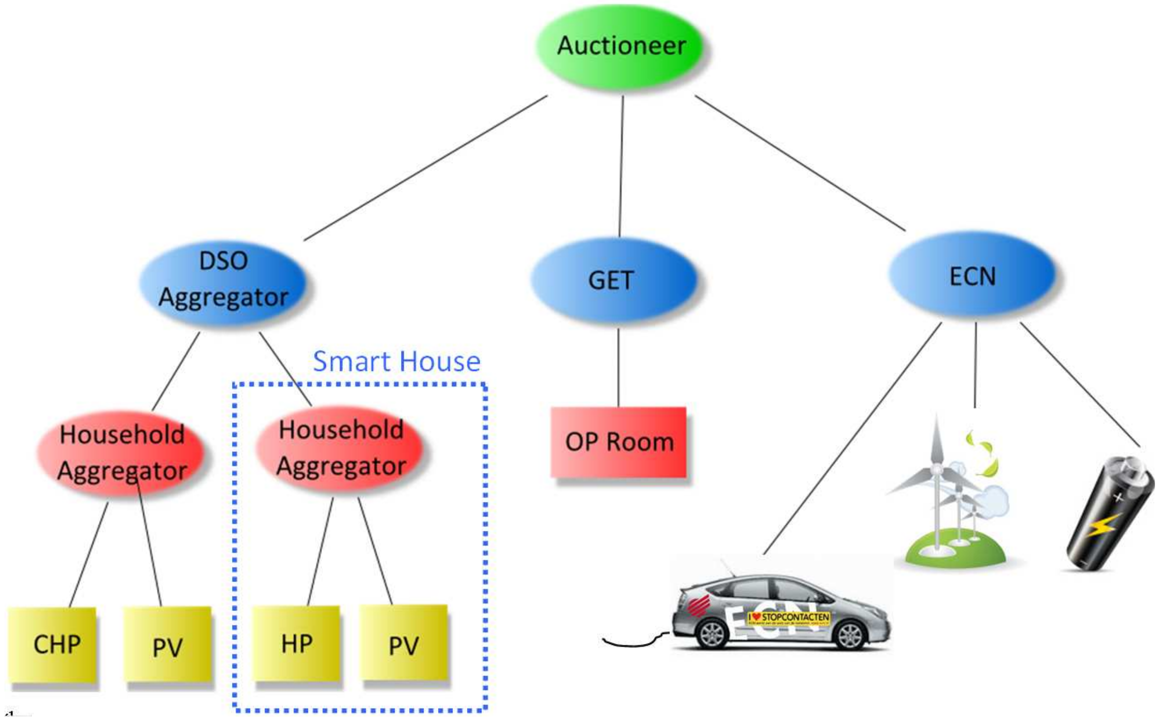


Figure 1 PowerMatching City schematic structure

The working name of this project is ‘PowerMatching City’, named after the control concept.

3.1 Evaluation method

As described in Integral deliverable 8.1 [D8.1], the extended ISO9126 standard for software quality was adopted as framework for evaluating the system architecture. The ISO9126 describes software quality in terms of ‘main characteristics’ and ‘sub characteristics’.

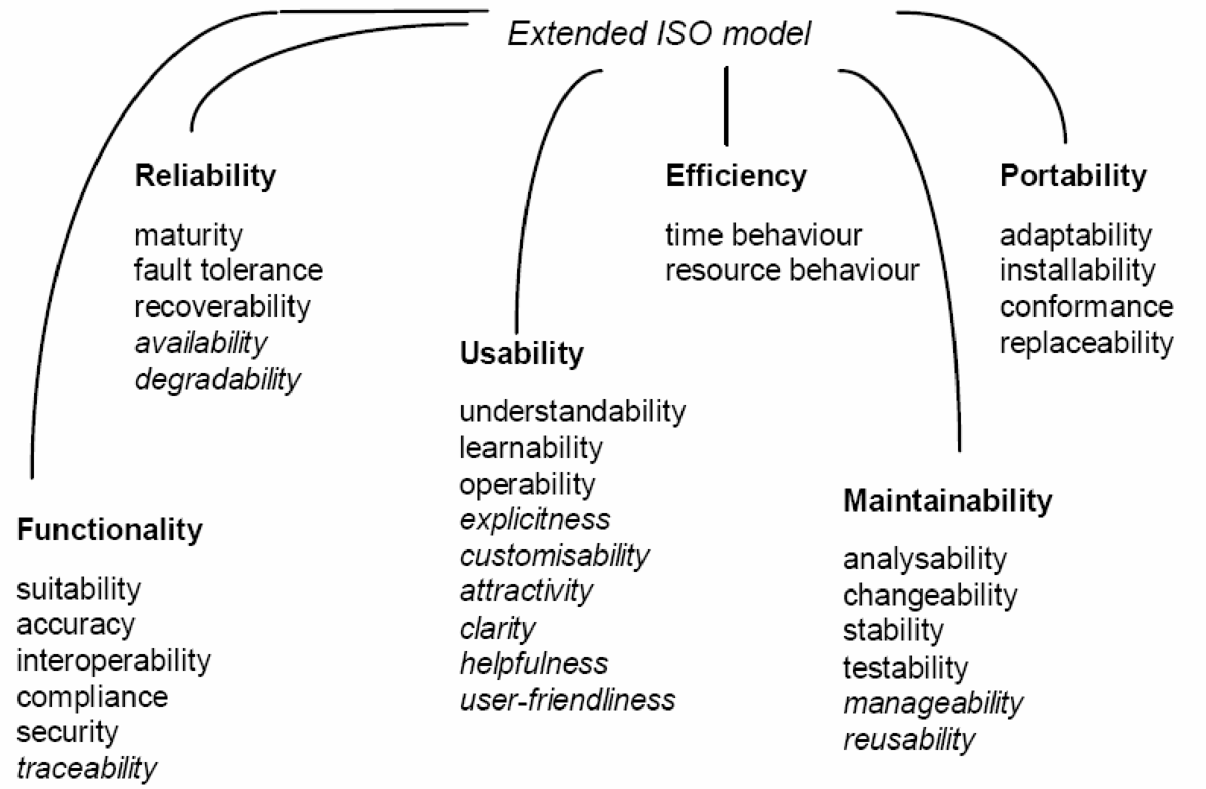


Figure 2 Overview of the extended ISO9126 main characteristics subdivided in sub characteristics

Not all quality characteristics can be implemented in software. Some characteristics conflict with others. For example providing an extended help function in the software for improving the characteristic 'understandability' will have a penalty on the characteristic 'resource behaviour'. Therefore, as a first step a selection is made of the most important quality characteristics.

For each of the selected quality characteristics it is indicated how this characteristic has affected the system and software architecture and infrastructure.

Finally, this document reports on the results in practice with respect to these characteristics.

3.2 The system and software architecture

For controlling the cluster of households a system was developed as described in the Architectural Design Description.

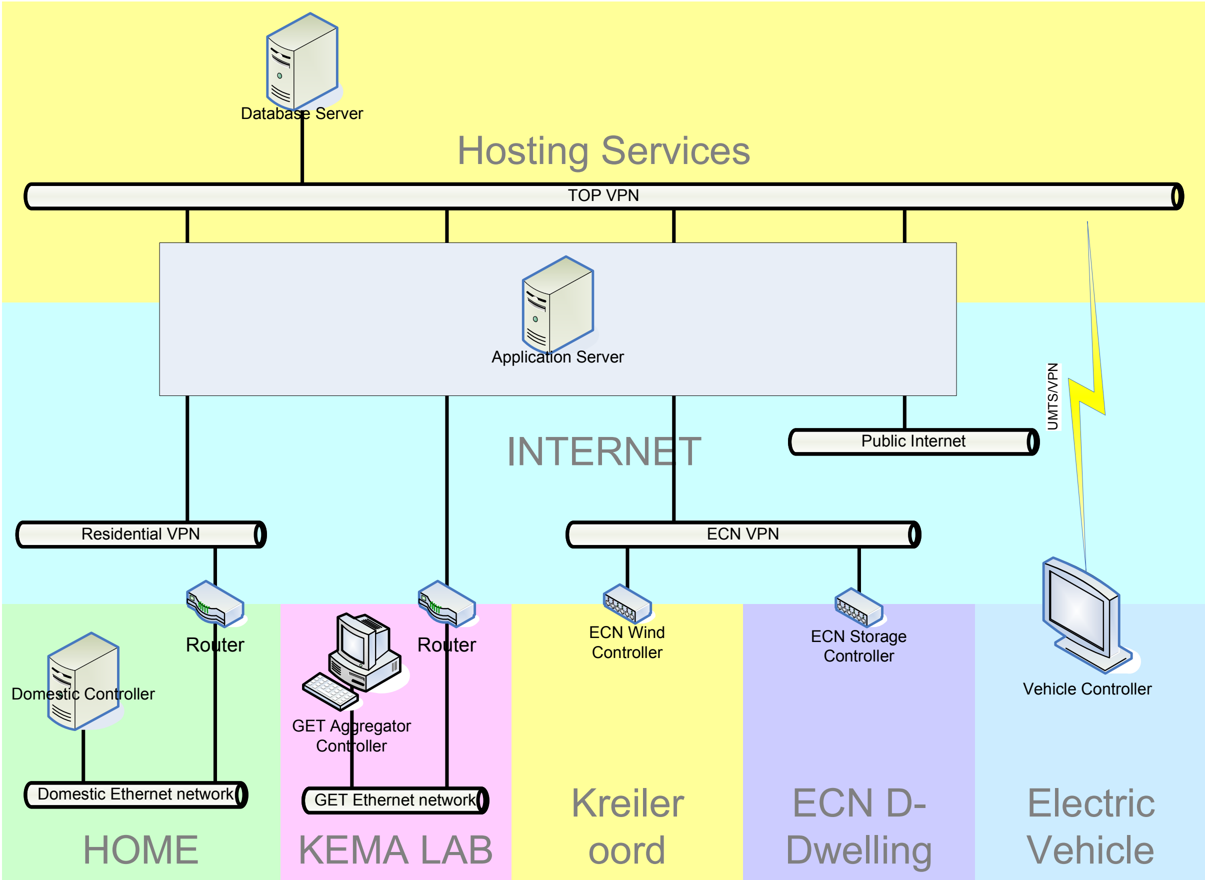


Figure 3 Network infrastructure

Figure 3 shows the network infrastructure. The components in the field test were connected by means of a dedicated VPN. To be independent from existing data channels in the household, a dedicated ADSL connection was provided to the house.

Following sections are visible by means of coloured blocks:

Section	Description
HOME	This section represents one household. The domestic controller is a small form-factor PC responsible for running the PowerMatcher Agents in the household.
KEMA LAB	The KEMA lab represents the laboratory facility at the KEMA premises. In this facility a number of demo set-ups have been created, each representing a household.
Kreileroord	At the Kreileroord the wind turbine is stationed. A controller was used to disclose the wind turbine to PowerMatching City.
ECN D-Dwelling	The D-Dwelling is a test house of ECN. It is a real house, only it is not inhabited. The house has got an electrical storage facility.
Electric vehicle	This section represents an Electric Vehicle. Three electrical vehicles were incorporated in the field test (two full electrical cars from

	Essent, one plug-in Hybrid from ECN). The controller in the car is a touch screen car PC. The connection consists of a VPN connection over UMTS.
INTERNET	The internet is used for • transport medium for the VPNs • Give access to the user portal by the households
Hosting Services	The Database Server and Application Server were hosted by a hosting provider. This party was also responsible for the VPN connections and the ADSL connections to the home.

Two main servers were used:

Server	Description
Database server	The database server only runs the Microsoft SqlServer database that is used for centrally collecting
Application server	The application server has a multitude of functions: • It offers the User Portal providing web page based information for the participating consumers. • It runs the Operator Portal for the system operator • It runs the PowerMatcher Auctioneer • It runs a number of PowerMatcher Concentrator, a.o. the one for the DSO • It runs the Commercial Aggregator Agent The reason for having all the applications on one server was that it was less expensive than having dedicated servers for each application. Performance was ample on the server.

Figure 4 shows details in the household. It contains two sections:

Section	Description
Domestic Ethernet Network	Secure domestic network.
Internet	The public internet used as carrier for the secure VPN connection to the central system.

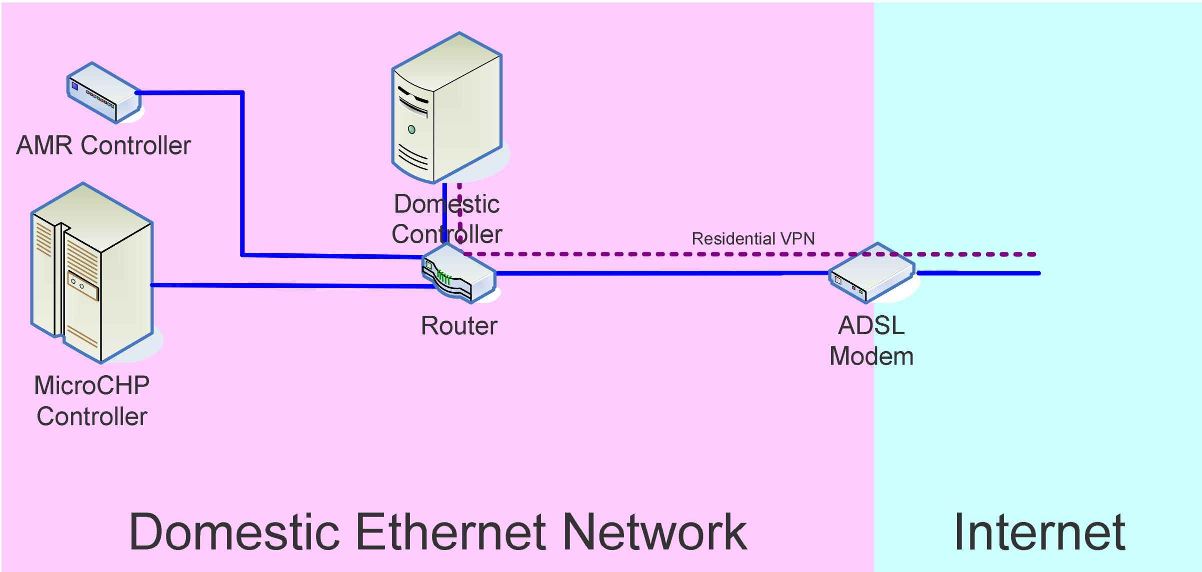


Figure 4 Infrastructure in the household

Component	Description
ADSL Modem	The modem connecting the Domestic Ethernet Network to the internet
Router	Dedicated router supporting VPN connection to outside.
Domestic Controller	The 'Household Controller'. It is a small form factor DELL PC, running Windows XP. It executes the local storage (Microsoft SqlServer database) and the PowerMatcher agents.
MicroCHP Controller	Controller responsible for controlling the MicroCHP. It is a Crouzet PLC.
AMR Controller	Controller for Automatic Meter Reading. The readout of M-Bus based electricity, gas and heat meters is done on the Domestic Controller. The AMR Controller converts requests by the Domestic Controller to M-Bus.

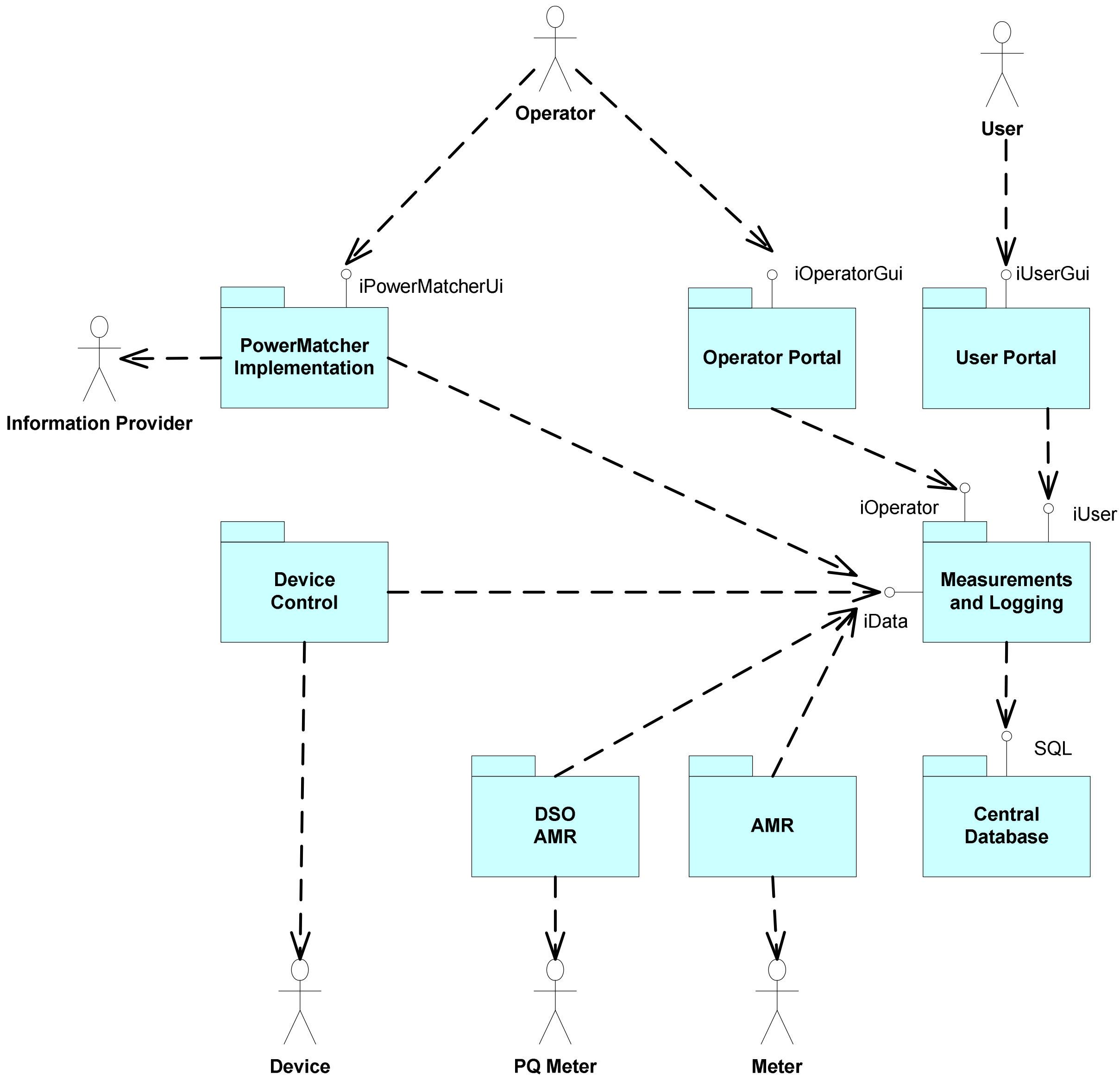


Figure 5 Software Architecture

Figure 5 shows the software architecture. The architecture is built around the Measurements and Logging component. This component is responsible for data storage, as well as communication between PowerMatcher Agents and the actual devices. It consists of a central data storage on the Database Server as well as a local storage on the Domestic Controller as is shown in Figure 6.

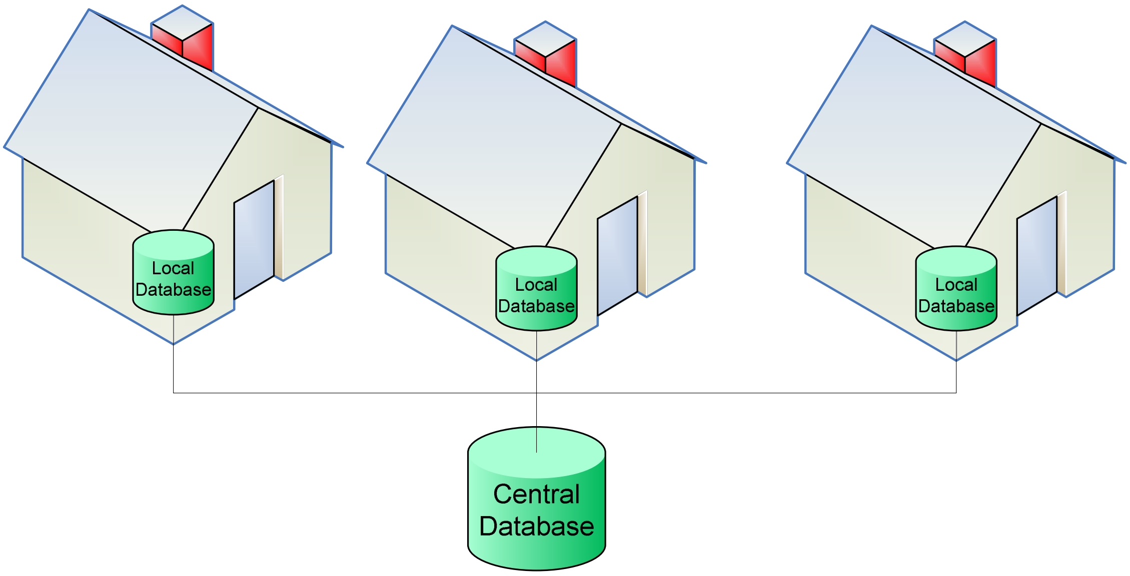


Figure 6 Central and Local Data storage together form the Measurement and Logging component

Device Controllers (responsible for controlling the actual devices, like the MicroCHP and Heat Pump) and AMR components measure and store data. PowerMatcher Implementation components use the stored data to provide incentives to the devices and store these incentives. The Operator Portal and User Portal provide views on the stored data. The Central Database component is formed by the Microsoft SqlServer database.

3.3 Results

3.3.1 Extended ISO9126 quality characteristic selection

This section describes the quality characteristic that were relevant for the system architecture of Work Package 5.

main ➔ sub characteristic	Motivation
Reliability ➔ Fault tolerance	The system implementing the smart grid is concerned with providing commodities to the consumer, like electricity and comfort. The system interacts with devices of the consumer. Currently the availability and reliability of these commodities is high. The system will become more complex. However, it may not lead to deterioration of commodity service. The system must therefore be fault tolerant: if one component or function fails, it must not lead to deterioration of the rest of the system.
Functionality ➔ Security	Data involved can potentially disclose a lot of information about the consumer and must be regarded as privacy sensitive. Therefore any data transaction must be secure.
Functionality ➔ Compliance	In order to create smart grids in which devices are operated from a large number of manufactures, standards (preferably open standards) must be applied. Where standards don't exist, standardisation must take place.
Portability ➔ Replaceability	Components in smart grid must be replaceable, preferably by similar components from other manufactures. This keeps cost low by preventing vendor lock-in.
Useability ➔ User-friendliness	Smart Grid technology must be available to everybody. Interaction of the user with the system must be user-friendly.
Maintainability ➔ Scalability	This is not an official characteristic of the extended ISO9126 model However it has been added by SmarTEST [ISO9126-3].

Note: There may be other quality characteristics that are important for a large scale roll-out of smart grids (e.g. Efficiency ➔ Resource behaviour may become important in order to keep device costs low), however during the PowerMatching City field test focus lay on the characteristics in the table.

3.3.2 Provisions per quality attribute

This section describes the provisions that were made for each quality attribute:

<u>Reliability ➔ Fault tolerance</u>

- All device controllers were constructed in such a way that when communication fails, it falls back to a default mode guaranteeing comfort.
- Where possible watchdog and keep-alive mechanisms were used. If a component fails (hangs up) a watchdog mechanism resets the component. A keep-alive

mechanism is used to detect malfunctioning components.

- Each software component reports to the central system by means of status-messages. If a component fails, it no longer sends this message. The central system reports this component 'missing', so the operator can take action find the cause of the problem.

- Software of controllers in the household could be remotely updated at the push of a button.

- By means of a remote terminal function the operator could log in on the controller in a household for monitoring and solving of problems.

Functionality ➔ Security

- A dedicated ADSL line was used for each household for the field test. No interference exists with other domestic data traffic.

- No WIFI connections were used in the household.

- All external data traffic (between household and central systems) was over a VPN. ZyWALL Products from Zyxel were used, utilizing DES, 3DES and AES encryption and IPSec NAT traversal for VPN. These are regarded as state-of-the-art security provisions.

- The Central Database was fully shielded by means of a firewall, the Application Server was operated from a 'Demilitarized Zone' (DMZ), shielded by a firewall. This is common practice for this kind of solution where access to portals is provided to the public internet.

- Access to the user portal is granted from every machine on the internet. Access to the operator portal is only possible from machines with a specific IP number.

- Access to the portals is shielded using username and password.

Functionality ➔ Compliance

- The software architecture used to implement PowerMatching city adheres to standard layered architectures which are for example described by Microsoft [MSARCH].

- Standard database technology is used.

- Standard protocols are used, like SOAP web services, XML and SQL.

- PowerMatcher technology is used. PowerMatcher is a concept in which different devices and stakeholders communicate in a highly standardised way. Different stakes (for example the stake of a MicroCHP device and the stake of Commercial Aggregator) are translated by the PowerMatcher Agent to standardised bids on a virtual commodity market.
  It is to be expected that the PowerMatcher technology will be turned in an industrial standard.

Portability ➔ Replaceability

- As stated PowerMatcher technology is used as unifying method to couple different devices and stakeholders. As long as a device adheres to the PowerMatcher standard, it can be added to the system or replace an other component.
- A layered architecture is used allowing to easily replacement of components. For example the Microsoft SqlServer database can be replaced by an Oracle database by reconfiguring the Hibernate component. Hibernate is a commercial component which is applied for making software objects persistent in the database.
- User Interface functionality was separated from business logic. This enables it to easily exchange the user interface.

Useability ➔ User-friendliness

- For devices like the MicroCHP and Heat pump the operation does not differ from an ‘uncontrolled’ device. Therefore the user does not have more interaction with a device than with a normal device.
- A user portal has been provided for the consumer. The portal offers insight in own energy consumption and own contribution to the grid. The participating consumers have been involved in the development of the portal.
- For the Electric Vehicles, the owner must indicate when he needs the car and what he expects from the battery (how full it must be). A touch display is in the car where he can enter this.

Maintainability ➔ Scalability

- The PowerMatcher concept defines ‘Concentrator’ components as means of scalability. A Concentrator represents all devices in underlying PowerMatcher networks as if it were just one device.
  During the project it several PowerMatcher networks have been created to show this scaling functionality.

3.3.3 Results in practice

This section presents the results classified by quality characteristic.

Reliability ➔ Fault tolerance

- Apart from some issues with the heating equipment no households were left in the cold.
- By means of the Operator Portal the Operator has overview of the system. This proved a valuable means of controlling the system. The Operator Portal is described in a separate section (section 3.4).
- The possibility to update software during operation life proved to be valuable. Bugs could be resolved quickly, improvements could be made.

Functionality ➔ Security

- The VPN network worked fine. During the operational period, the VPN server at the hosting side was exchanged, without problems.
- No security issues were reported.
- Though for the portals plain HTTP was used for the User Portal and Operator Portal, it might be better in future to use HTTPS in order to shield privacy sensitive data exchange.

Functionality ➔ Compliance

- Apart from the provisions for compliance mentioned in 3.3.2, no additional effort was made to prove compliance.

Portability ➔ Replaceability

- As will be explained in the section about the Operator Portal (section 3.4.3 and 3.4.4), new devices could be defined. PowerMatching City could be easily extended. As an example: during the field test it was decided to also incorporate Electric Vehicles from Essent. This proved no problem.
- The data model that was used (described in **Erreur ! Source du renvoi introuvable.** and reflected in the Operator Portal as described in section 3.4.3 and 3.4.4) proved generic enough to be able to describe devices used and to define PowerMatching City.
- During the field test it has been shown that the information available on the central server can be made accessible on multiple user interfaces. The information accessible on the car touch screen has been made visible on a third party touch terminal in the house.

Useability ➔ User-friendliness

- Several feedback sessions were organised in order to collect feedback from the consumers on the User Portal. The User Portal appeared to be sufficient for the Consumers.
  However, investigation into improving the portal was made by M.C.M. Vos-Vlamings. Please refer to [MVV].

Maintainability ➔ Scalability

- Bandwidth required per household typically was 8 kBit/s (or 1kByte/s) for downloading as well as uploading, as is shown in Figure 7. A typical download speed offered by an ADSL provider is 800 kByte/s, the upload speed is 80 kByte/s. Compared to this, the system consumes 0.13 % of the available download bandwidth and 1.3% of the upload bandwidth.

  The peaks in the graph correspond to synchronisation between local and central storage. It must be noted that for the sake of the experiment more data is exchanged than strictly necessary to control the smart grid.

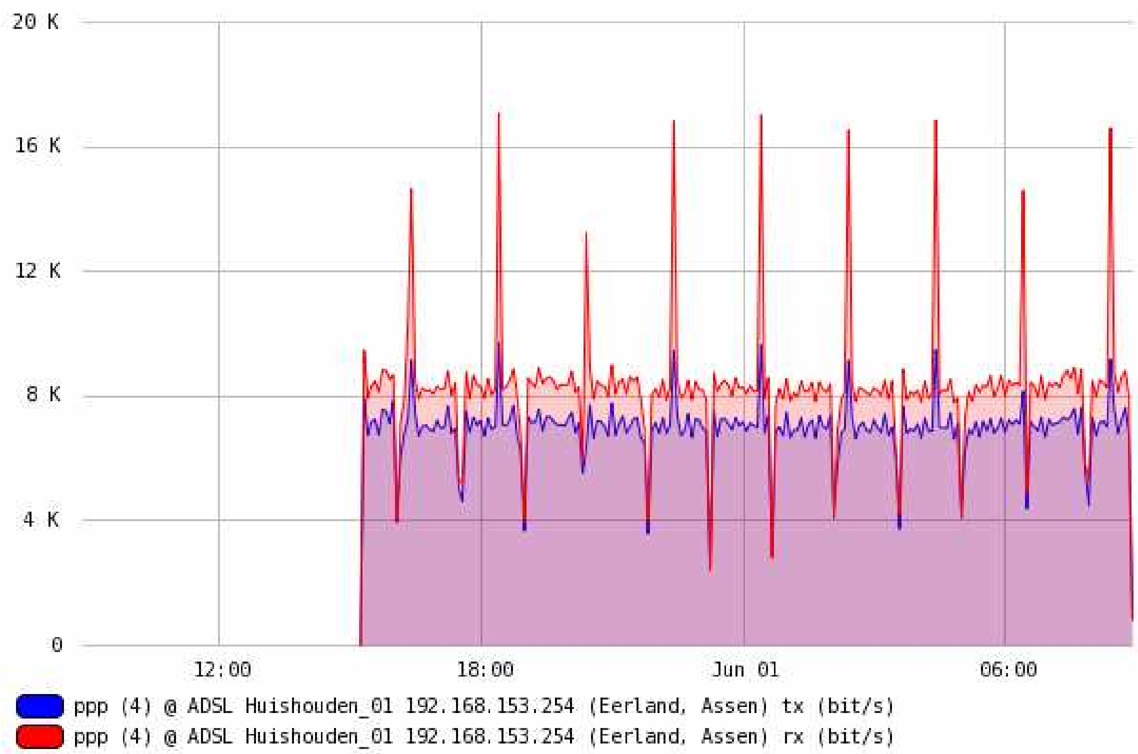


Figure 7 Bandwidth usage for a household

- Database performance appeared to highly depend on good design practice, like the use of indices and caching. Several improvements were made to keep the performance sufficient. Note that for this field test a lot more information was collected and stored for analysis compared to what is strictly necessary for operation.

3.4 Operator Portal

An important tool to manage the PowerMatching City field test is the Operator Portal. By means of this tool the Operator was able to monitor and configure the system.

3.4.1 System Overview

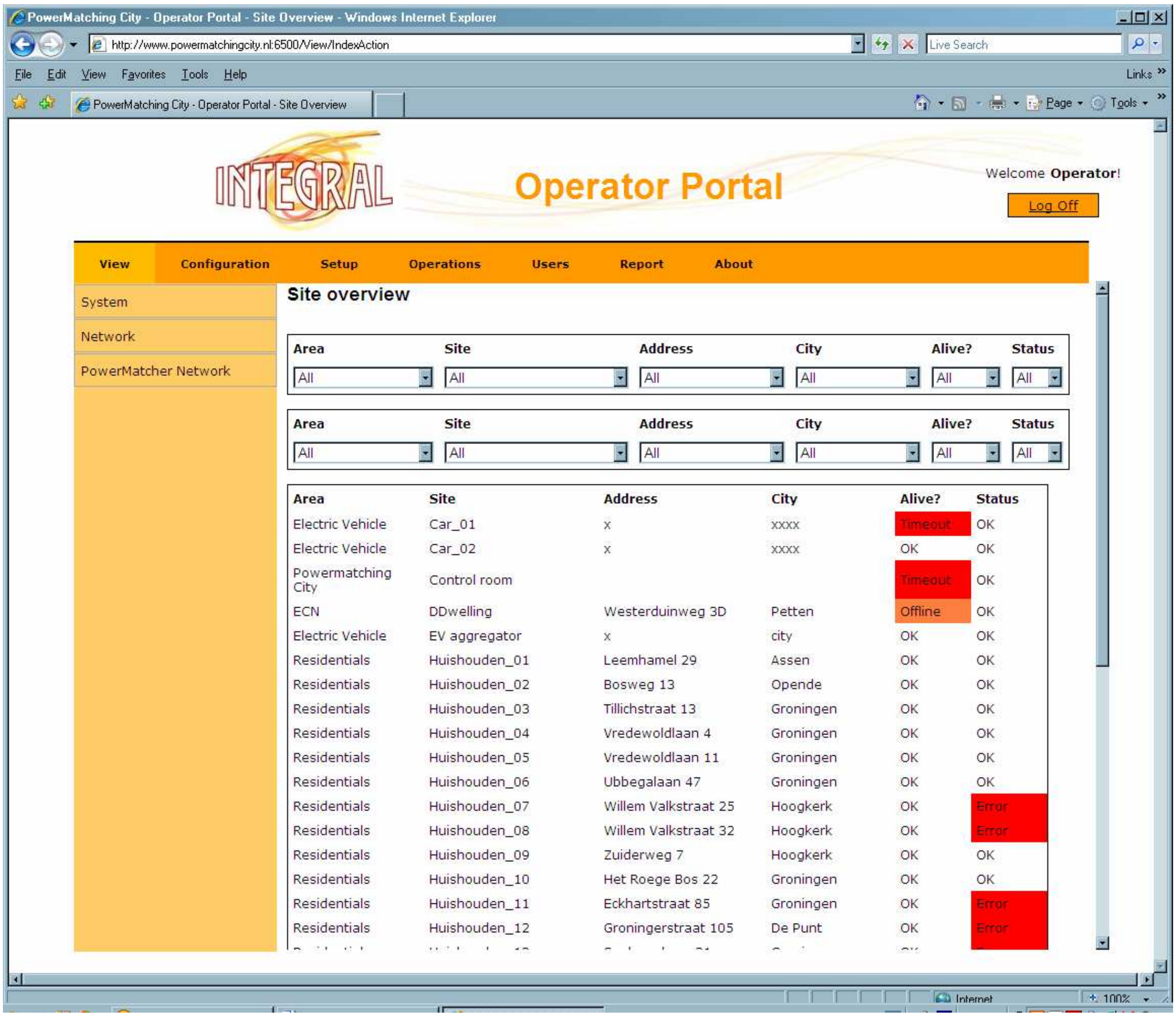


Figure 8 Operator Portal system overview

Figure 8 shows the system overview. The system overview shows the status of all sites. The last two columns in the overview show the status.

The '*Alive?*' value indicates whether keep-alive messages have been received from *all* software components on the site. A keep-alive message is periodically sent. If a component malfunctions or a network connection fails it keep-alive messages are no longer received by the central system and the site will report a 'timeout'. For example, the Electric Vehicle Car_01 is parked and is not being charged. The controller in the car switches off (in order not to deplete the battery).

The ‘Status’ value indicates whether there is one (or more) software component(s) that report an error.

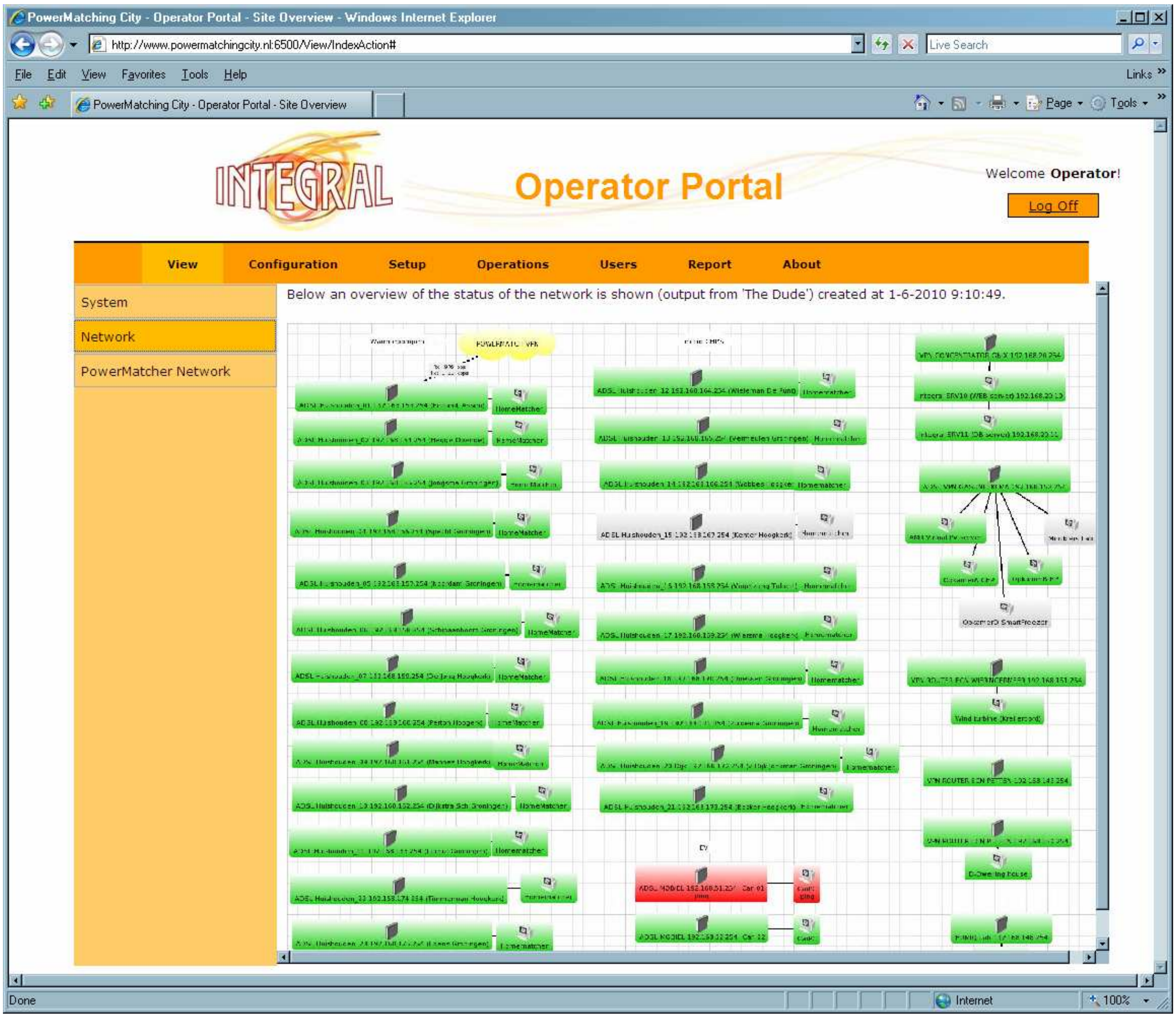


Figure 9 Operator Portal network overview

Figure 9 shows the network overview as provided by the hosting provider. The overview is integrated in the Operator Portal. It shows for all VPN network nodes whether they are up-and-running.

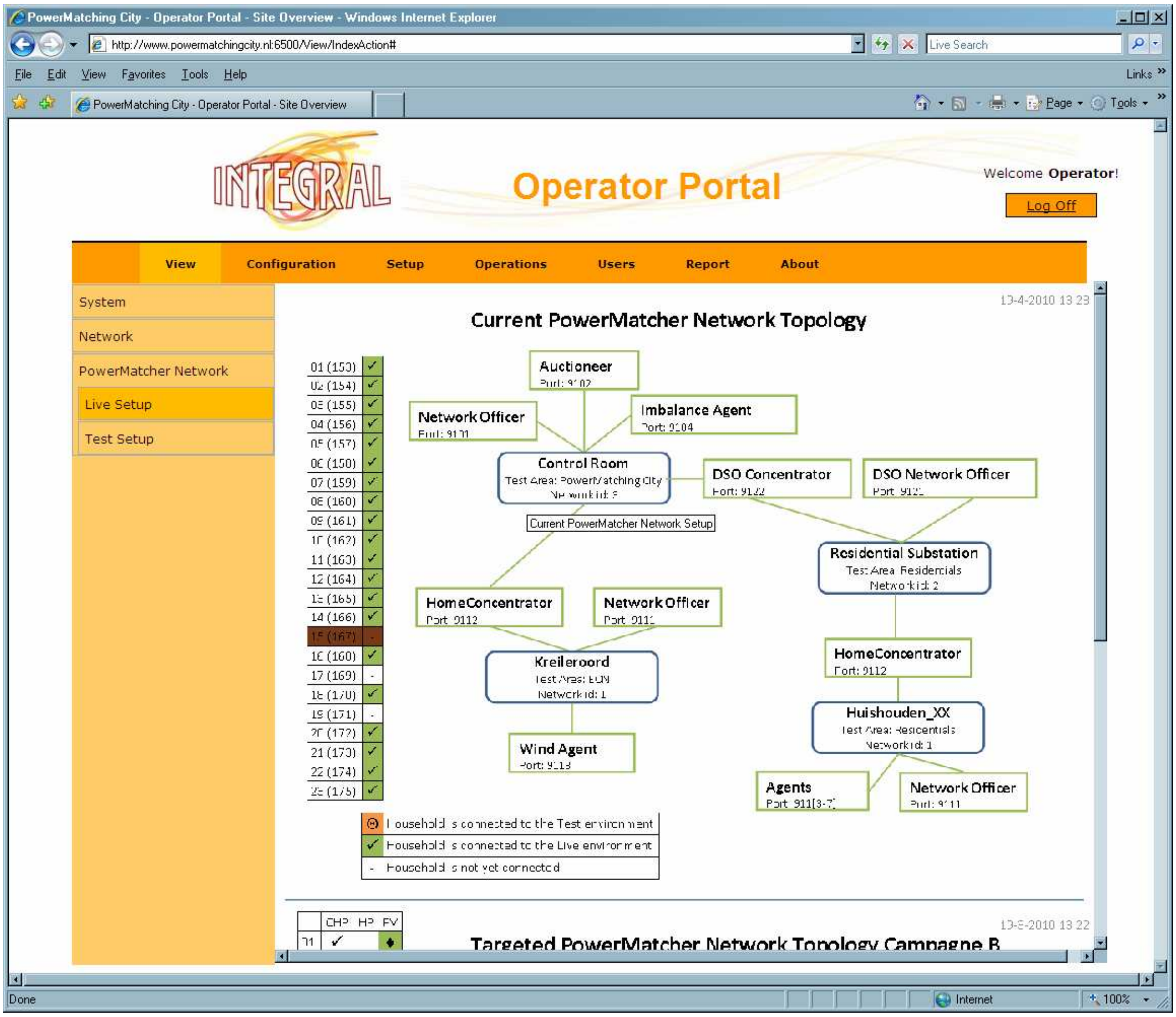


Figure 10 Operator Portal PowerMatcher configuration

Figure 10 shows the configuration of PowerMatcher components. It is a static picture that is meant as reminder how the network is configured.

3.4.2 Configuration of devices

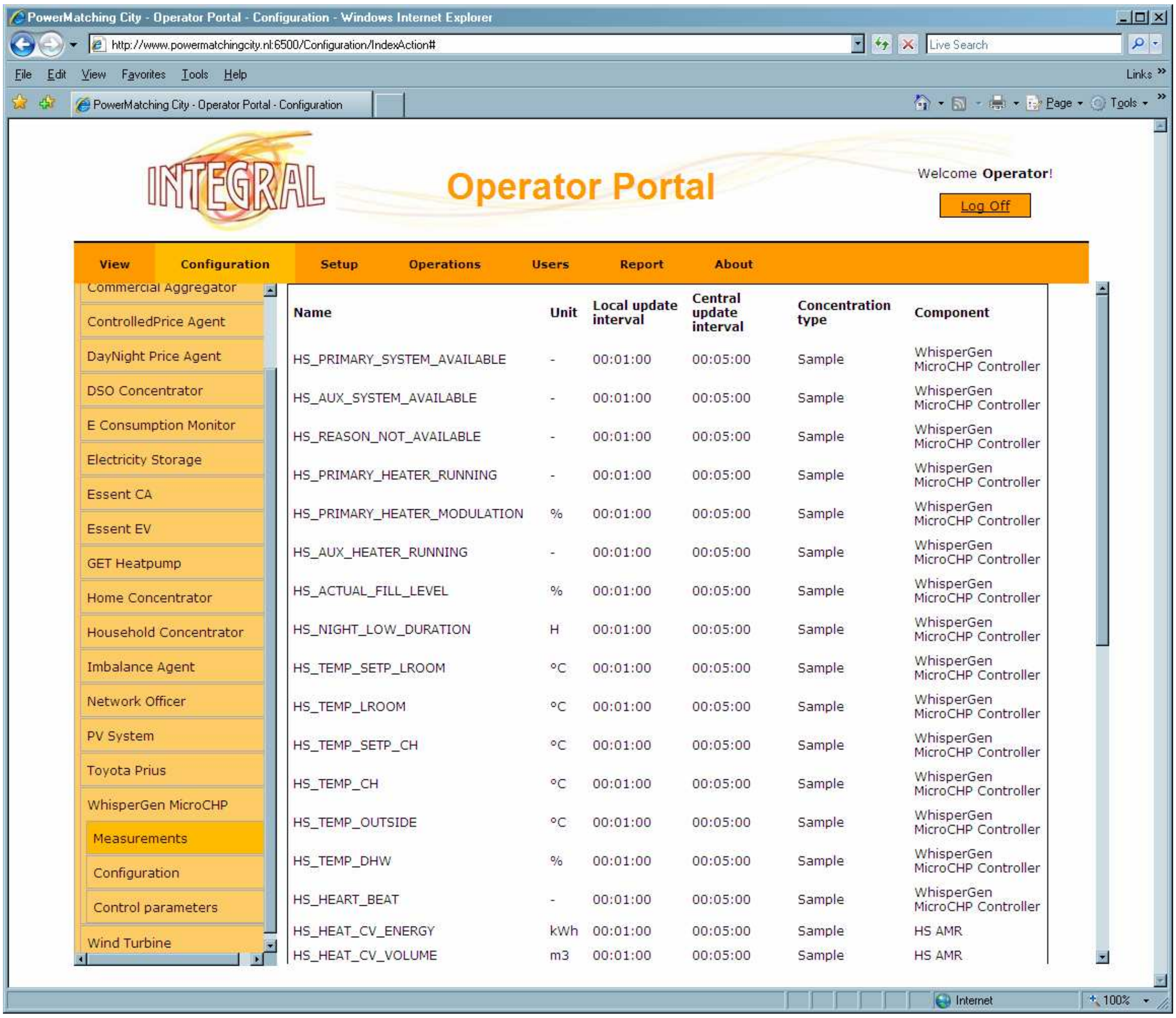


Figure 11 Operator Portal device configuration

Each possible device and its software components in the system have to be configured. A definition is made of

- the measurements a device component can perform
- the configuration parameters that are available for a device component
- the control parameters that can be used to control a device component

3.4.3 Setting-up PowerMatching City

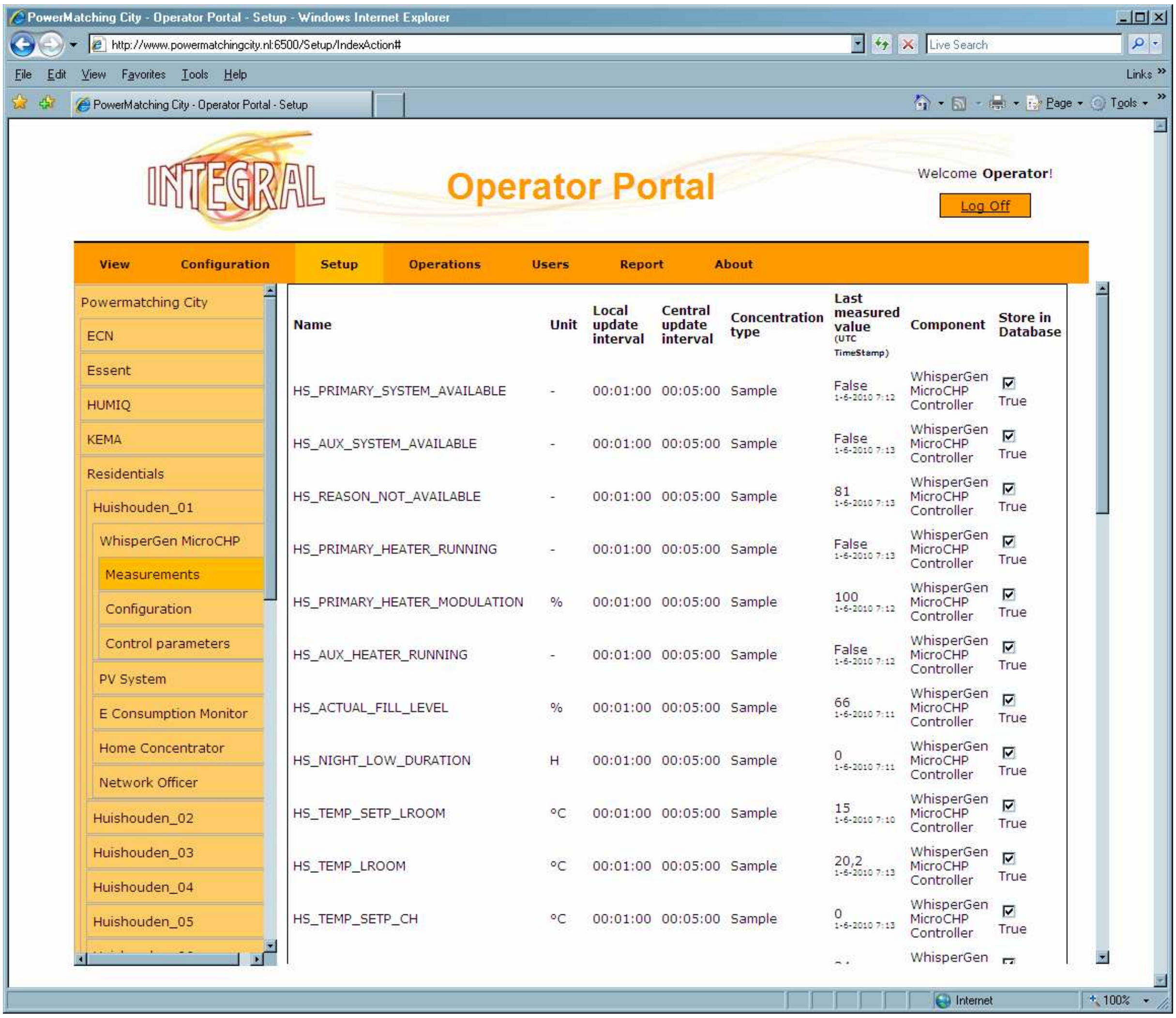


Figure 12 Operator Portal PowerMatching City setup

Figure 12 shows the set-up of PowerMatching City. To the left a hierarchical overview of the entire field test is visible. It starts at the top level with 'PowerMatching City'. From there the test areas are visible like 'KEMA' and 'Residentials'. In each area the test sites are visible, like 'Huishouden_01' (Household_01). For each test site the devices are shown, like 'WhisperGen MicroCHP'. Finally, per device the Measurements, Configuration Parameters and Control Parameters are presented.

Measurements can be configured (at what interval the value must be measured). The last measured value is presented.

Configuration Parameters can be presented and modified. Configuration is modified at the central system and synchronised to the local systems.

Last value of the Control Parameters can be presented. Control Parameters are defined to enable one software component to control another. For example, a MicroCHP Agent may use a Control Parameter to order the Device Controller to switch on the MicroCHP device. The Control Parameters are used locally at each site. Once every few minutes the Control Parameter values are sampled and sent to the central system.

3.4.4 Maintenance of PowerMatching City

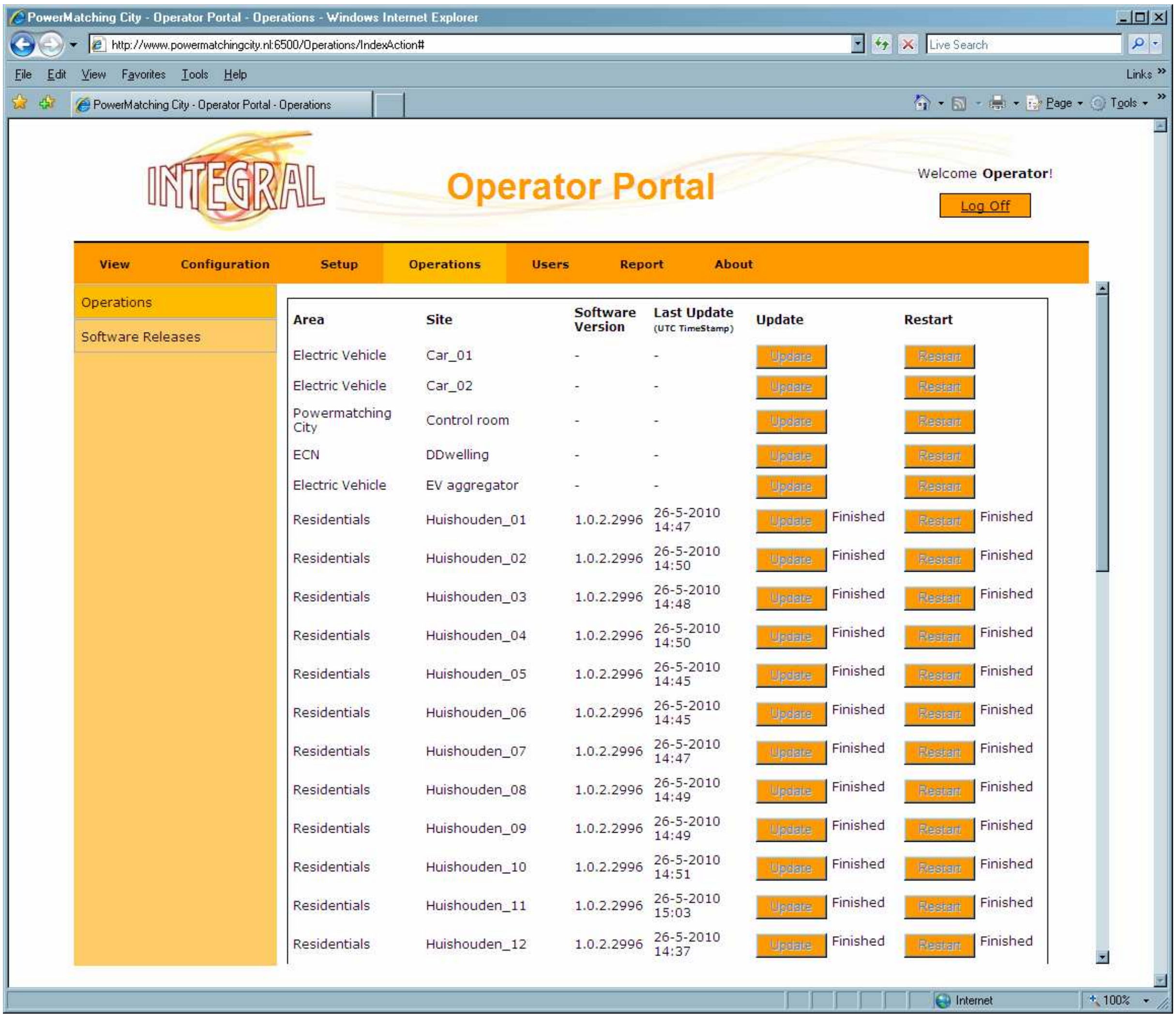


Figure 13 Operator Portal: Software update and restart

Figure 13 shows the ‘Operations’ section of the Operator Portal. From here the software at individual sites can be updated and/or restarted.

3.4.5 Reporting

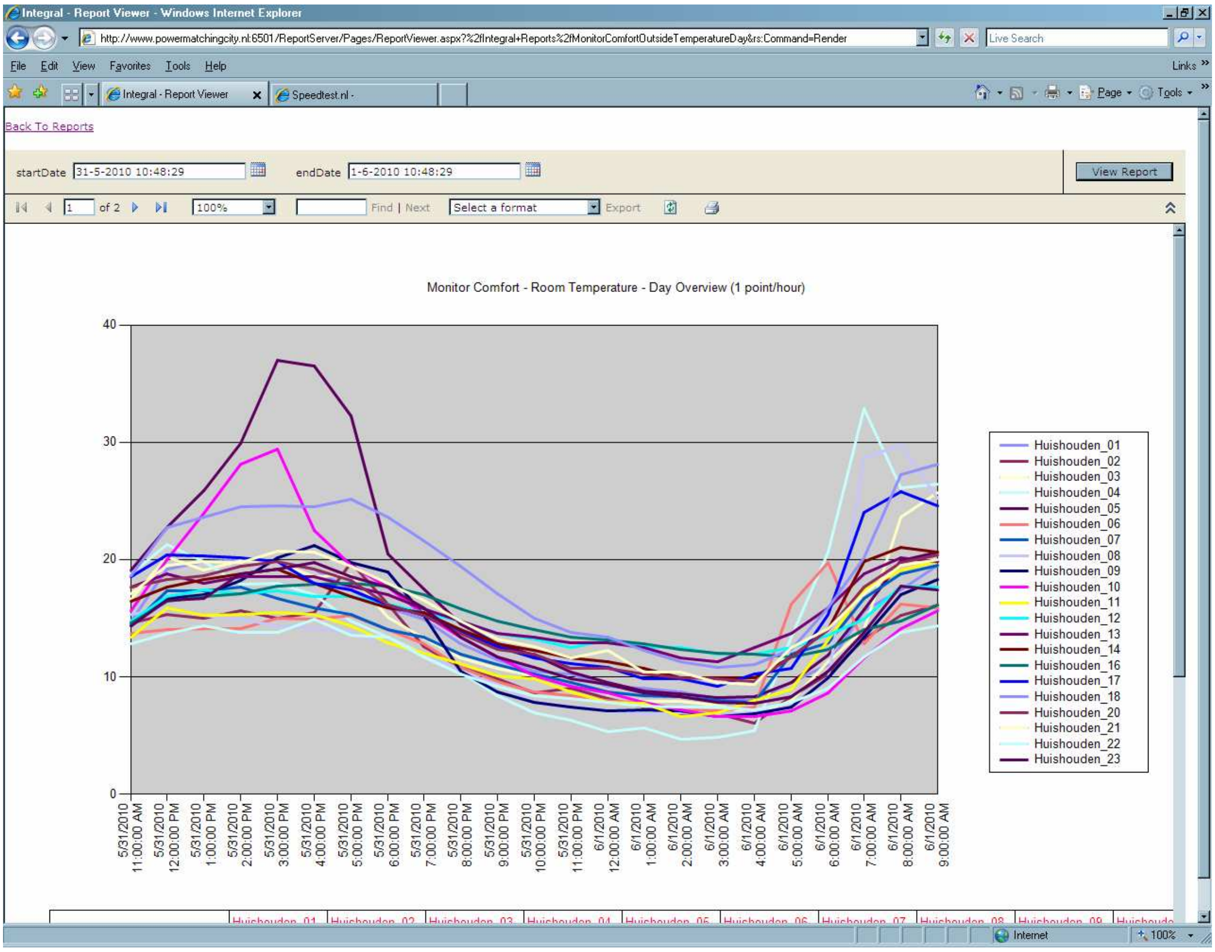
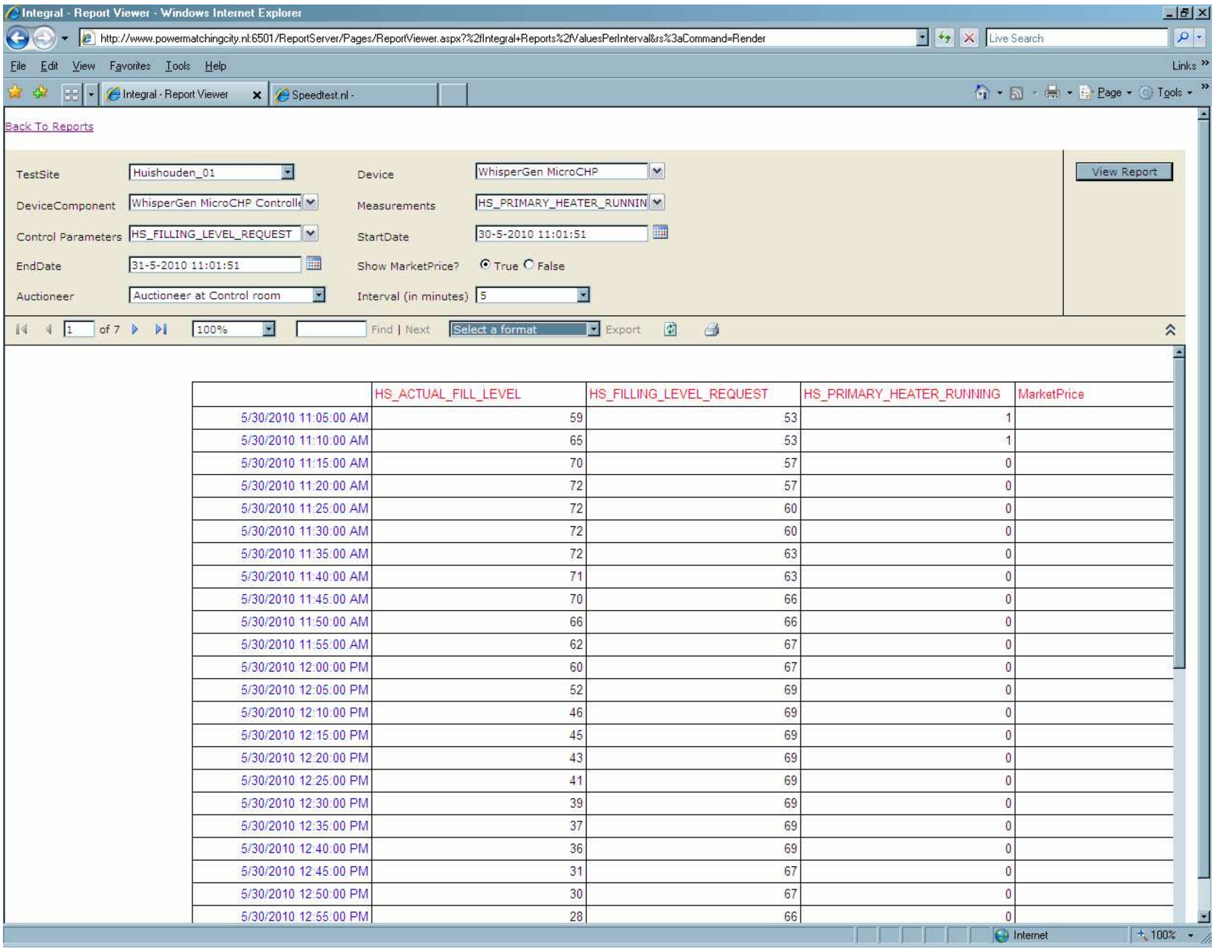


Figure 14 Reporting service

In order to disclose the experimental data that is collected, Sql Reporting Services were used. An example is shown in Figure 14, this graph shows the outside temperature as measured at each participating household over one day.

A number of predefined reports were available. It is also possible to create own graphs, as is shown in Figure 15. By means of drop-down boxes selection of parameters and period can be created.

Data can be shown in a graph or table. Data can also be exported in different formats, for example XML, CSV or Microsoft Excel format. This data can be processed for example in Microsoft Excel or Matlab.



	HS_ACTUAL_FILL_LEVEL	HS_FILLING_LEVEL_REQUEST	HS_PRIMARY_HEATER_RUNNING	MarketPrice
5/30/2010 11:05:00 AM	59	53	1	
5/30/2010 11:10:00 AM	65	53	1	
5/30/2010 11:15:00 AM	70	57	0	
5/30/2010 11:20:00 AM	72	57	0	
5/30/2010 11:25:00 AM	72	60	0	
5/30/2010 11:30:00 AM	72	60	0	
5/30/2010 11:35:00 AM	72	63	0	
5/30/2010 11:40:00 AM	71	63	0	
5/30/2010 11:45:00 AM	70	66	0	
5/30/2010 11:50:00 AM	66	66	0	
5/30/2010 11:55:00 AM	62	67	0	
5/30/2010 12:00:00 PM	60	67	0	
5/30/2010 12:05:00 PM	52	69	0	
5/30/2010 12:10:00 PM	46	69	0	
5/30/2010 12:15:00 PM	45	69	0	
5/30/2010 12:20:00 PM	43	69	0	
5/30/2010 12:25:00 PM	41	69	0	
5/30/2010 12:30:00 PM	39	69	0	
5/30/2010 12:35:00 PM	37	69	0	
5/30/2010 12:40:00 PM	36	69	0	
5/30/2010 12:45:00 PM	31	67	0	
5/30/2010 12:50:00 PM	30	67	0	
5/30/2010 12:55:00 PM	28	66	0	

Figure 15 Custom report

3.5 Recommendations for future research

Based on these findings we recommend following:

- During the project dedicated ADSL connections were used for connecting the household. The connection was dedicated for the project for the sake of reliability of the connection and not to be dependent on existing data channels that are under responsibility of the consumer.
  In practice this gave problems. Not all households were standard provided with a 2nd ADSL lines. Cables must be placed.
  It must be investigated what alternatives are available. To what extent can existing connections be used, which are less reliable (for example: a consumer may switch of his broadband modem at night time)? Will alternatives like UMTS/GPRS connections be an alternative dedicated data channel? Dutch telecom providers foresee an increase in M2M communication via UMTS/GPRS networks.

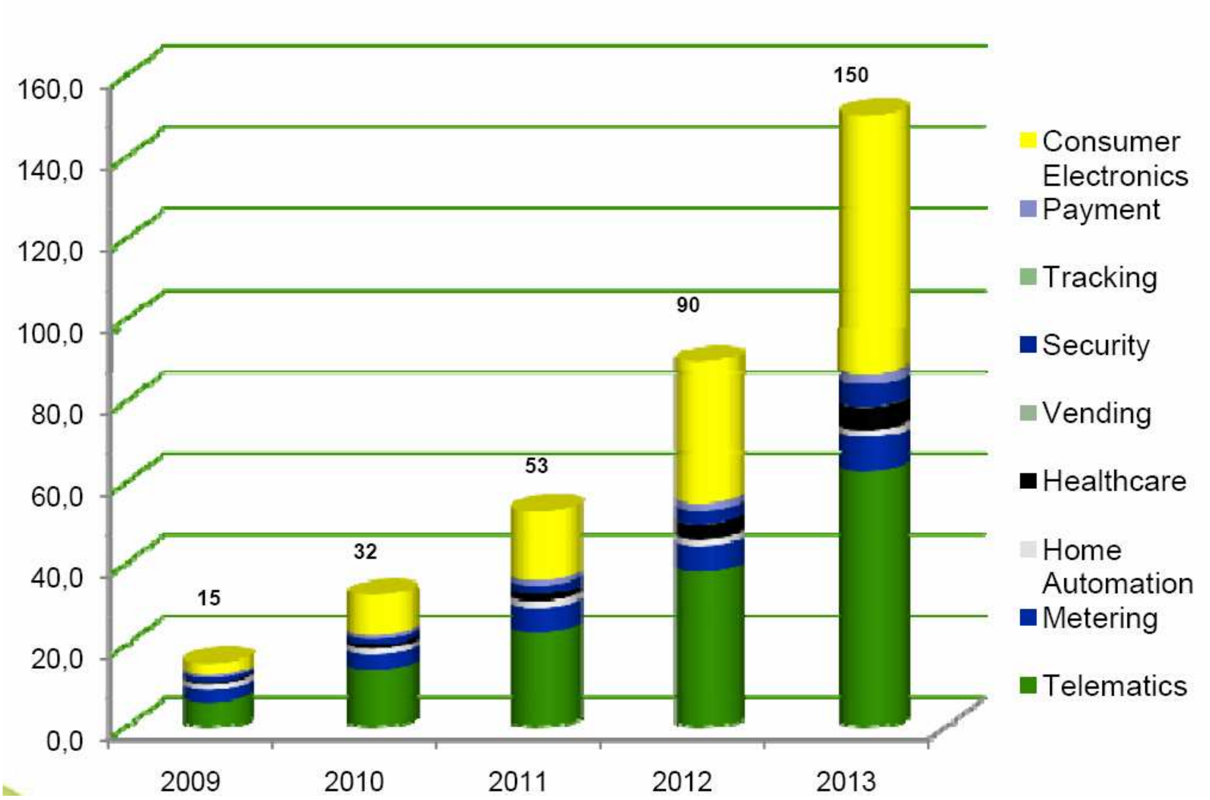


Figure 16 Increase in mobile connections for M2M applications: ten fold increase in 5 years (source: KPN)

- Though it has been shown that for the infrastructure COTS components could be used, costs per household were quite high. The reason was that high-end controllers were used and a dedicated, reliable and secure connection was used. Furthermore, the research character of the field test required facilities for extensive data storage. In a final solution such facilities can be omitted. These facilities have a drawback on the design and therefore on the costs of the field test set-up.
  Costs for a dedicated VPN based data connection were quite high. In future research investigation should be made whether VPN or VPN like technology can be integrated in the controller itself, without compromising security.
  In future research investigation should be made into the usage of low end embedded controllers.

- At the hosting side the Application Server executed a lot of different tasks. In large scale roll-outs the tasks must be split amongst multiple servers. There are two reasons:
  The first reason is that from a security perspective it is safer to separate services. A public web portal requires connection to the public internet, the other services do not. Therefore the other services shall be on a server shielded from the public internet. The second reason might be performance. For PowerMatching City server performance was not an issue. In large scale roll-outs it might become an issue. To cope with performance issues is done by load-balancing techniques in combinations with multiple servers.

- PHD Investigation has been made by M.C.M. Vos-Vlamings on how to create the best User Portal [MVV]. However, the results have not been implemented during the Integral project. For future projects, these results should be taken into account.

- In order deploy smart grids standardised interfaces are required on domestic devices for connecting them to and making them controllable in a smart grid. During the field test a lot of effort was spent to make commercial domestic devices (MicroCHP, heat pump, freezer, etc) controllable in the smart grid. Often this resulted in conflicts between existing control in the device and the control necessary for the smart grid.

- Though effort is made in standardising ‘smart meters’ a lot of work needs to be done here. M-Bus meters were deployed. It appeared that though M-Bus is a standard, large differences exists in protocol and capabilities between M-Bus meters. Even different batches of the same brand and type of M-Bus meter were found to contain different implementations of the M-Bus protocol, rendering part of the meters unusable.
  Meters complant to the Dutch NTA8130 meter standard often do not fulfil the smart grid requirements. For smart grids it is required to have real-time access to meter data. Often meter data is only available once per 24 hours. Also extra electricity meters for measuring gross production are often not included.

4. Evaluation of architecture and infrastructure for Demo B

4.1 Introduction

The scope of Demo B is the development of a control system that will enable the operation of parts of the grid under critical conditions (island mode, voltage/frequency instability). The software architecture and the hardware requirements of the test environment for Demo B have been extensively described in previous deliverables (D4.2). The results of implementation of the developed software (multiagent system) and hardware (ZigBee nodes) under different use-cases were presented and analyzed in deliverable D6.3&4.

This section describes the evaluation of the system architecture and infrastructure for Demo B. The experiment B critical operation field-test configuration is depicted in Figure 17. There is a Microgrid, consisting of a number of renewable energy based generators (PV, Wind turbine), and a number of shift-able loads related to domestic consumption like heating/cooling and lighting. There is a 220 V local grid, connected to two types of inverters including SMA-inverters, that are able to exert control actively in response to Voltage and frequency deviations, which may occur as a result of external or internal events. Within the Microgrid, not connected to the main grid, a separate place is reserved for additional equipment, which emulates external events (due to legislation in Spain, the Microgrid is not allowed to be physically connected to the main grid).

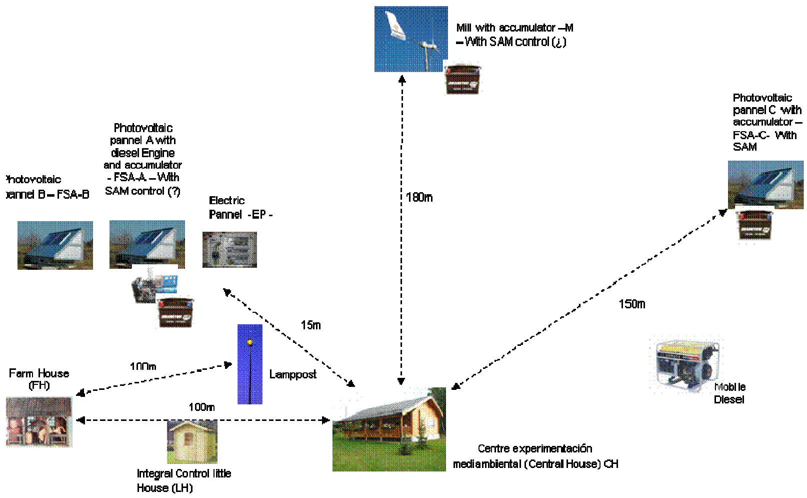


Figure 17 MAS Roig schematic structure

The system that was developed includes two main parts (Figure 18), the ZigBee controller and the MAS (Multi Agent System). The ZigBee part will focus mainly in controlling and monitoring the Loads in the real field. The ZigBee is the platform that executes the decisions and actions in the real world (connect / disconnect, regulate, measure, etc…), and the MAS system will focus mainly in monitoring and controlling after communication and deliverative process. Of course, each Agent will have its ZigBee node counterpart.

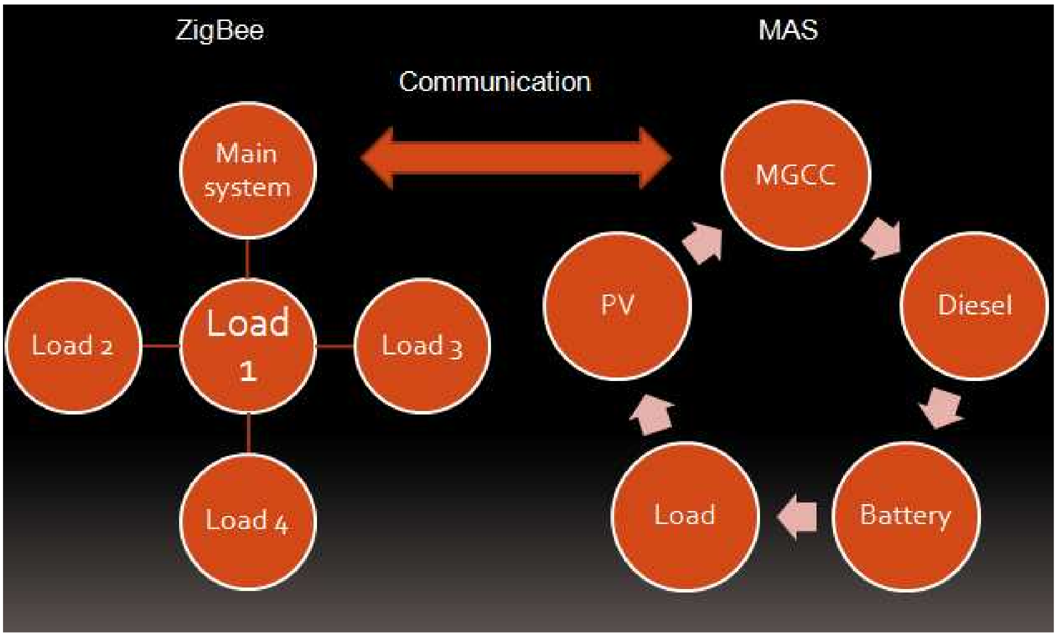


Figure 18 Representation of the system.

The ZigBee infrastructure is presented in Figure 19. Each ZigBee node controls one load and is responsible to transmit the measurements (voltage, current, frequency, active/reactive power, load status) from the consumption area to the ZigBee coordinator. The ZigBee nodes which have direct access to the ZigBee coordinator operate as transmitter for the distant ZigBee nodes so as to ensure the transmission of entire information. The ZigBee nodes are organized as a mesh network enabling the whole system to operate normally when one node breaks down or a connection goes bad.

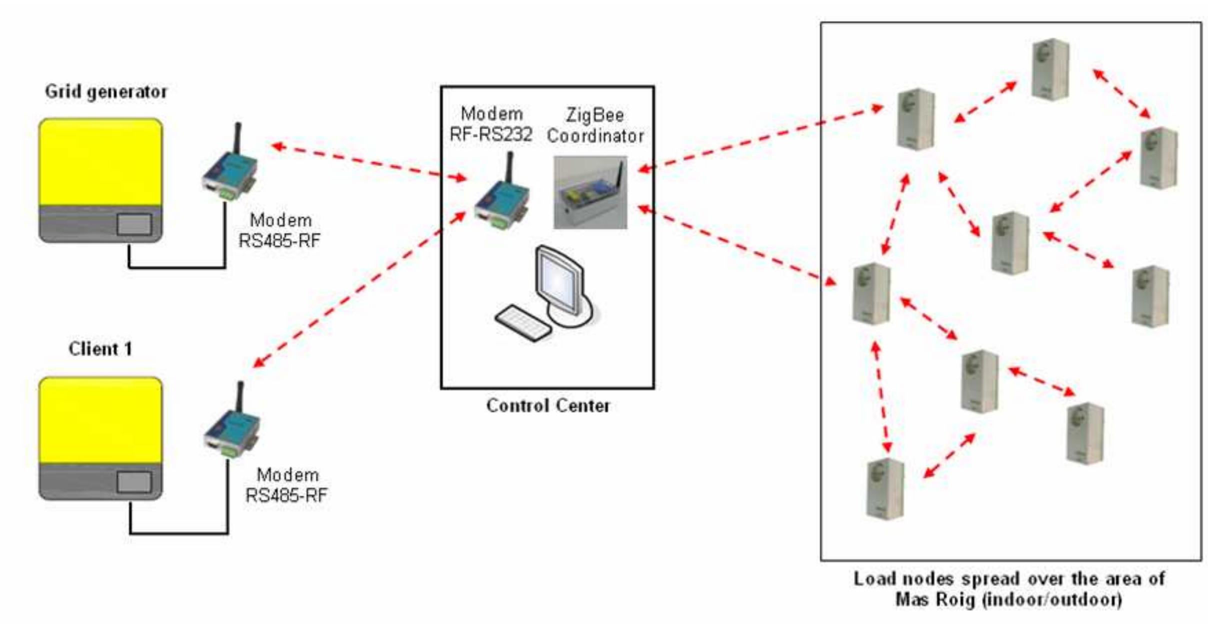


Figure 19 Communication Infrastructure

For the communication between the central PC and the inverters controlling the production units RF modems are used. The output measurements of the inverters are transmitted from the MODEM RS485-RF as radio frequency signals to MODEM RF-RS232. The output measurements are evaluated by the multi-agent software and new set-points are sent back to the inverters.

Each ZigBee node is represented by an agent in the multi-agent system. An agent is responsible for evaluating the measurements received from the ZigBee nodes and controlling the load accordingly. The agents' action is coordinated by central controller which has the overview of the system operation. The coordination of their action is achieved by the agent's ability to communicate with each other.

For each agent a graphical interface has been developed so as the user to be able to monitor the consumption and the status of the system. Figure 20 presents the graphical interface of the central controller agent where the users can have a general view of the system operation. The users can be informed about the total consumption of the system so they are aware of times they demand much energy. Users can also be informed about the maximum production of the distributed generators and adjust their consumption levels in order to utilize efficiently the green energy. When a grid imbalance is occurred, (frequency or voltage disturbance) the user is informed about the type of disturbance through coloured tabs as displayed in Figure 20. If the user is willing to see separately the status of each load, there is also a graphical interface for each load as presented in Figure 21. This interface enables the user to know which loads are operating or not and how much each load is consuming.

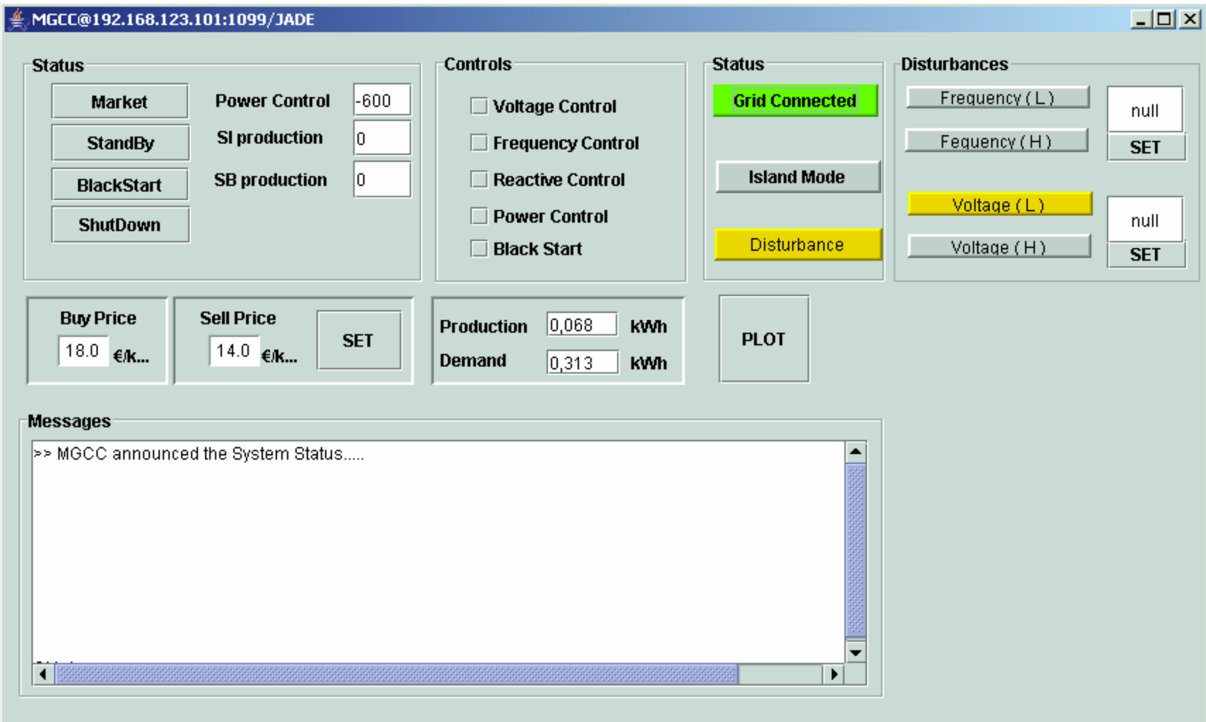


Figure 20 Graphical Interface of the agent of central controller

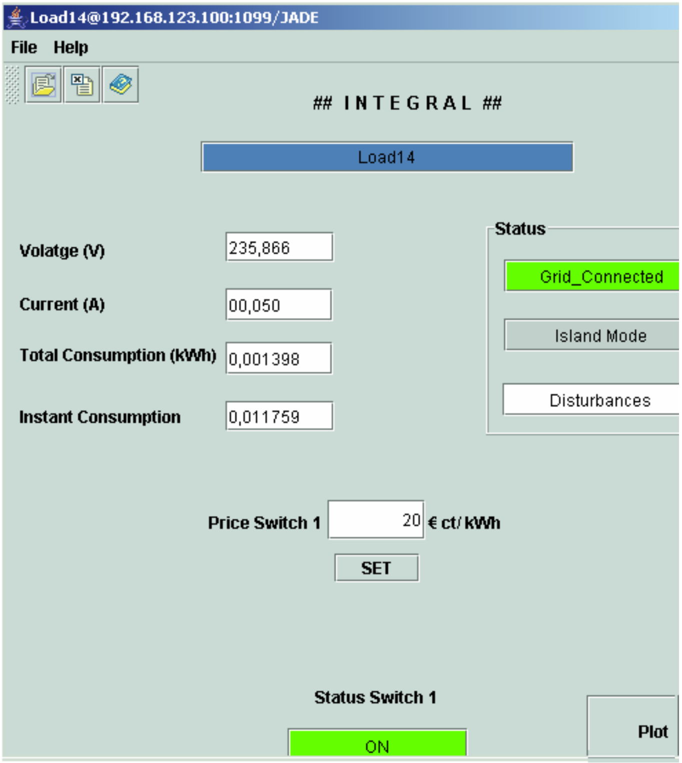


Figure 21 Graphical Interface of a load agent

4.2 Example of the system operation under critical conditions

The multi-agent system monitors the voltage in the field test in order to maintain it within specific limits. In case the local voltage exceeds these limits, then immediate action should be taken in order to support the grid. In case of a voltage drop, there is need for reduction of the local consumption. In case of low voltage drop, about 5% of the nominal value, the multi-agent system orders low priority loads to switch off. In case of deeper voltage drops (over 10%), medium priority loads should be disconnected as well.

Figure 22 presents the voltage and current profile of each load as measured by each ZigBee node respectively. Zero current means that either loads are shedded or there is no load connected at the specific ZigBee node at that moment. Demand can be varied according to house owner's preferences. For example, the consumption in load C increases at 18:09 due to the house owner's activity. There are ZigBee nodes (such as load E, F, H, I etc) which measure zero consumption because the devices they control are switched off by the house owner.

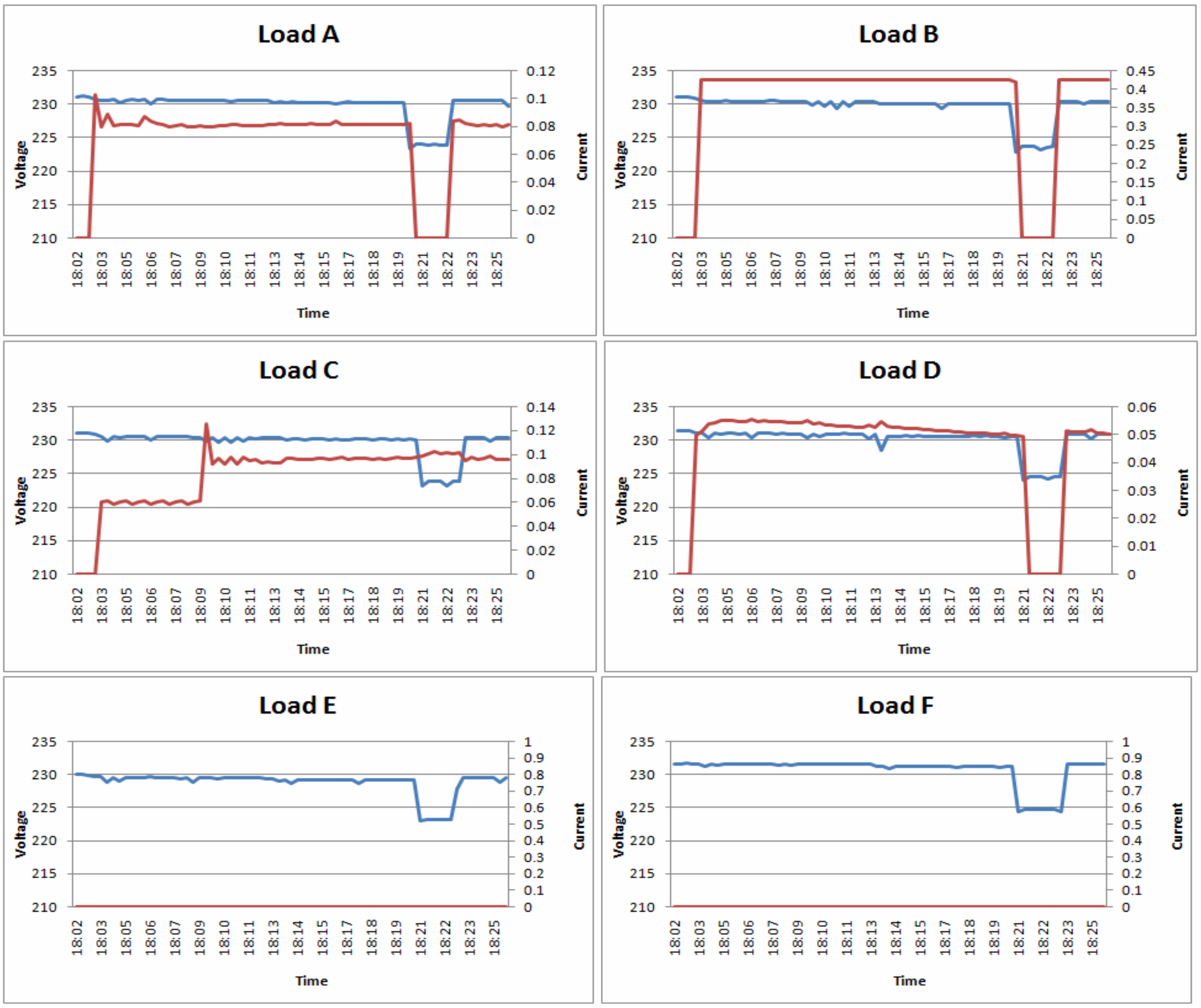


Figure 22 Voltage and current profile of every load as measured by each ZigBee node

Voltage: blue line and Current: red line (part 1)

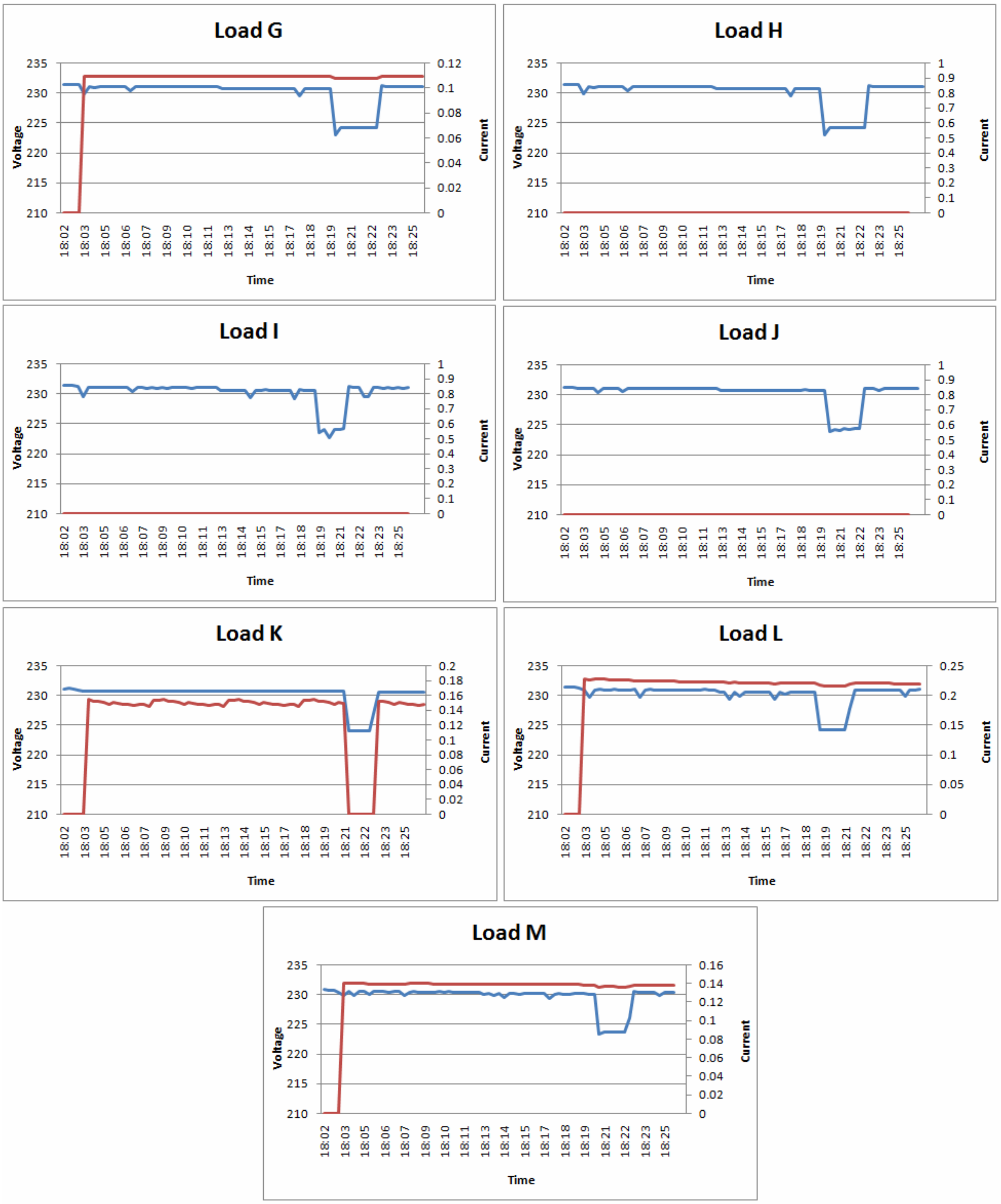


Figure 23 Voltage and current profile of every load as measured by each ZigBee node

Voltage: blue line and Current: red line (part 2)

In case of a low voltage drop the multi-agent control system curtails only the low priority loads. This is shown in figures 24, 25 and 26 where the status of the relay for each load (i.e. ZigBee node) according to their priority is presented.

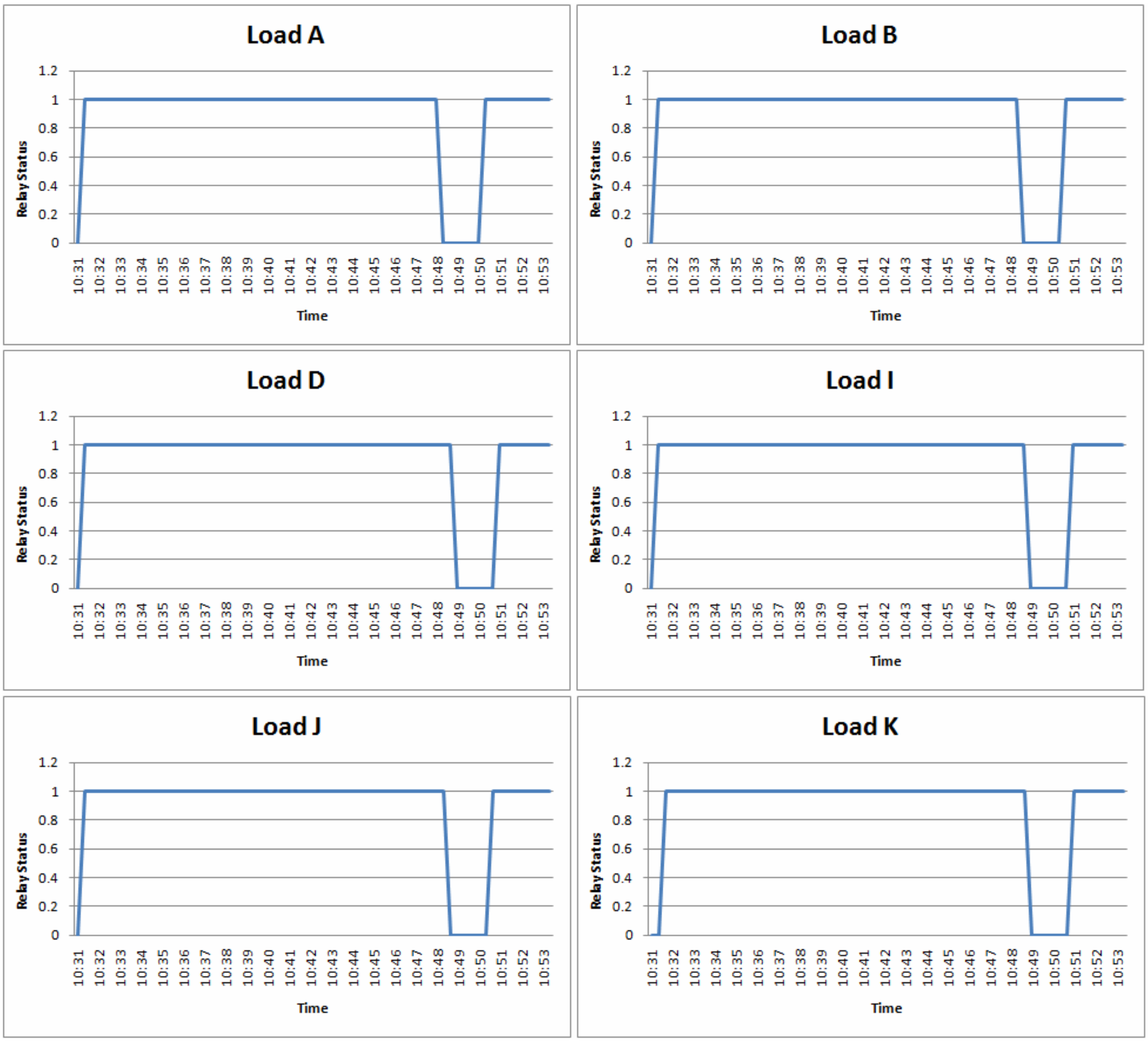


Figure 24 Status of relay for each load (i.e.ZigBee node) – Low Priority Loads

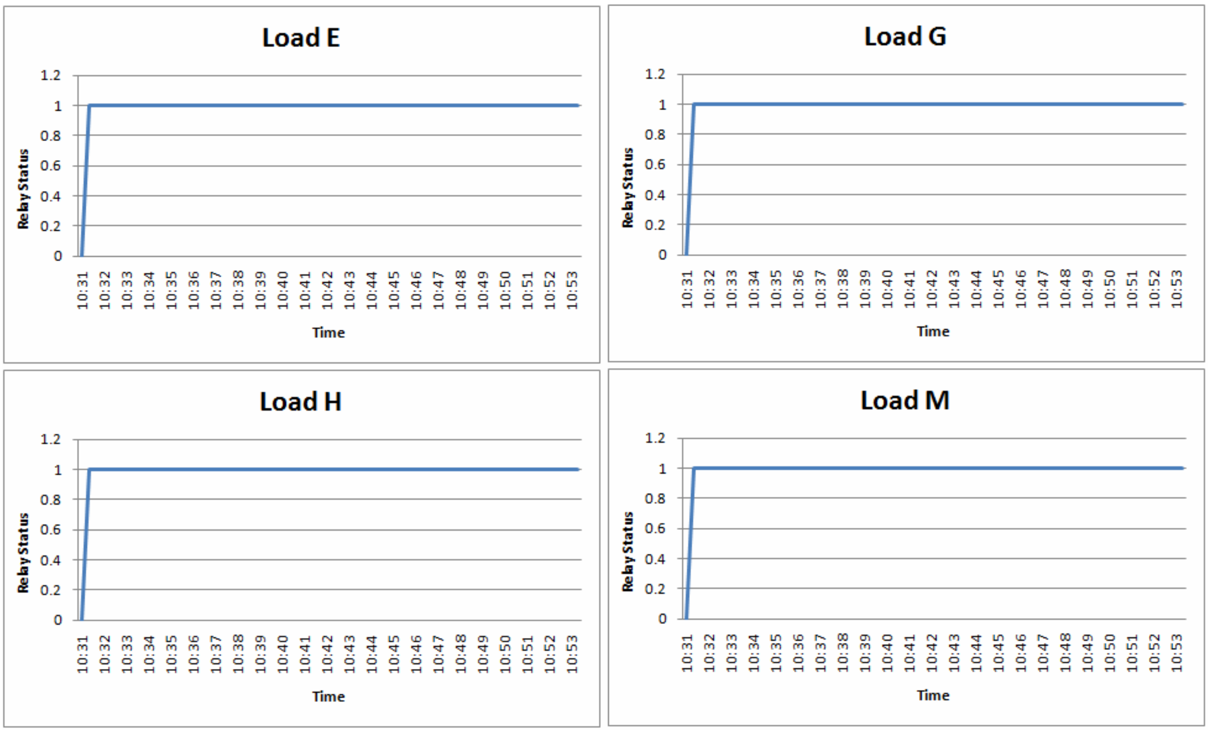


Figure 25 Status of relay for each load (i.e.ZigBee node) – Medium Priority Loads

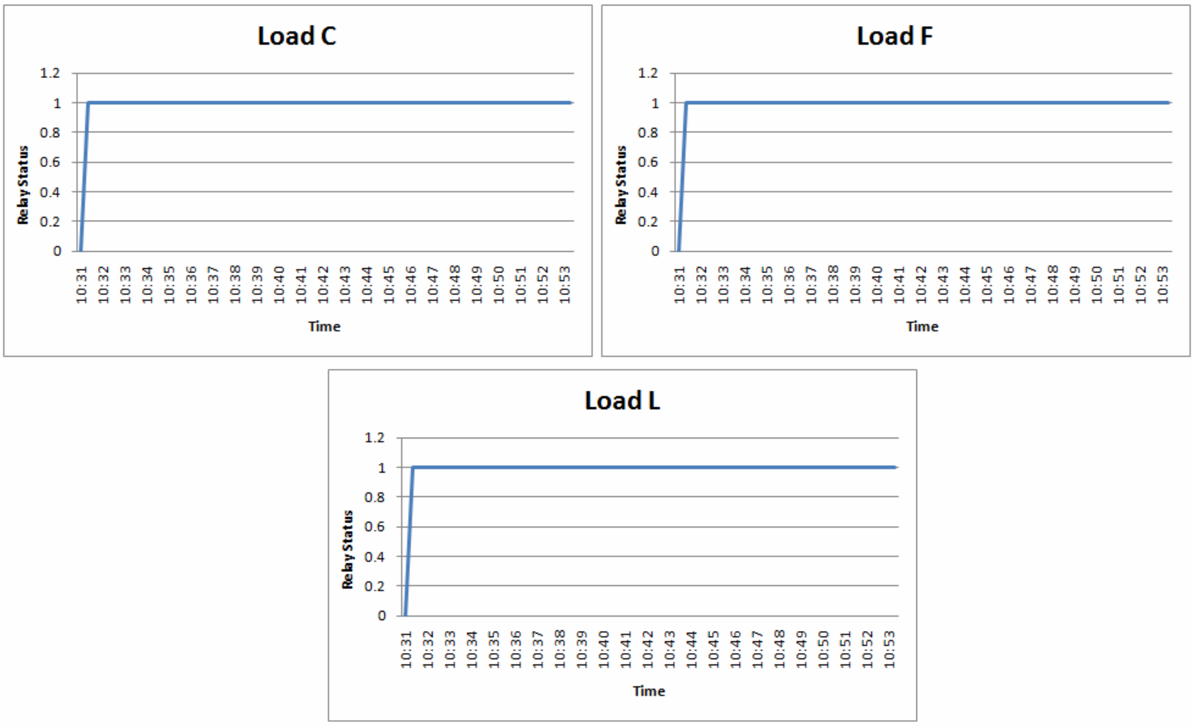


Figure 26 Status of relay for each load (i.e.ZigBee node) – High Priority Loads

Figures 27 and 28 present the results of a low voltage drop. The multi-agent control system detected a voltage drop through the agent's voltage monitoring capabilities. After the voltage disturbance has been recognized by an agent a message is sent to the MGCC in order to take action. In a very small local network area the voltage profile is similar for all the agents. If all the agents were developed with a voltage monitoring behavior then a number of identical warning messages would be sent to the MGCC. This may result in increased network traffic and reduce the speed of message exchanging and the efficiency of the multi-agent control. In order to avoid such a network traffic and since the local voltage profile is the same for all agents, only one agent was responsible for monitoring the voltage of the local network. In case of wider networks, there is need for a number of agents to be developed with voltage monitoring capabilities in order to monitor small local areas with same voltage profile. After the recognition of the voltage disturbance, the MGCC curtails the appropriate loads depending on the criticality of disturbance.

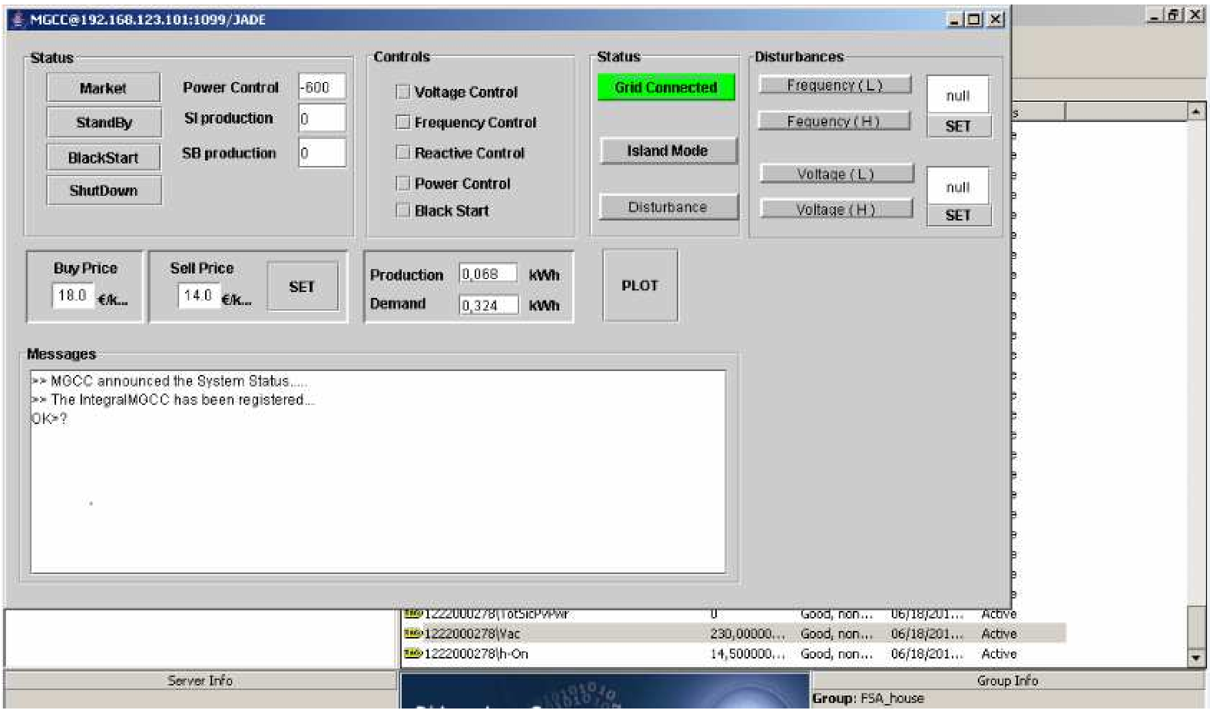
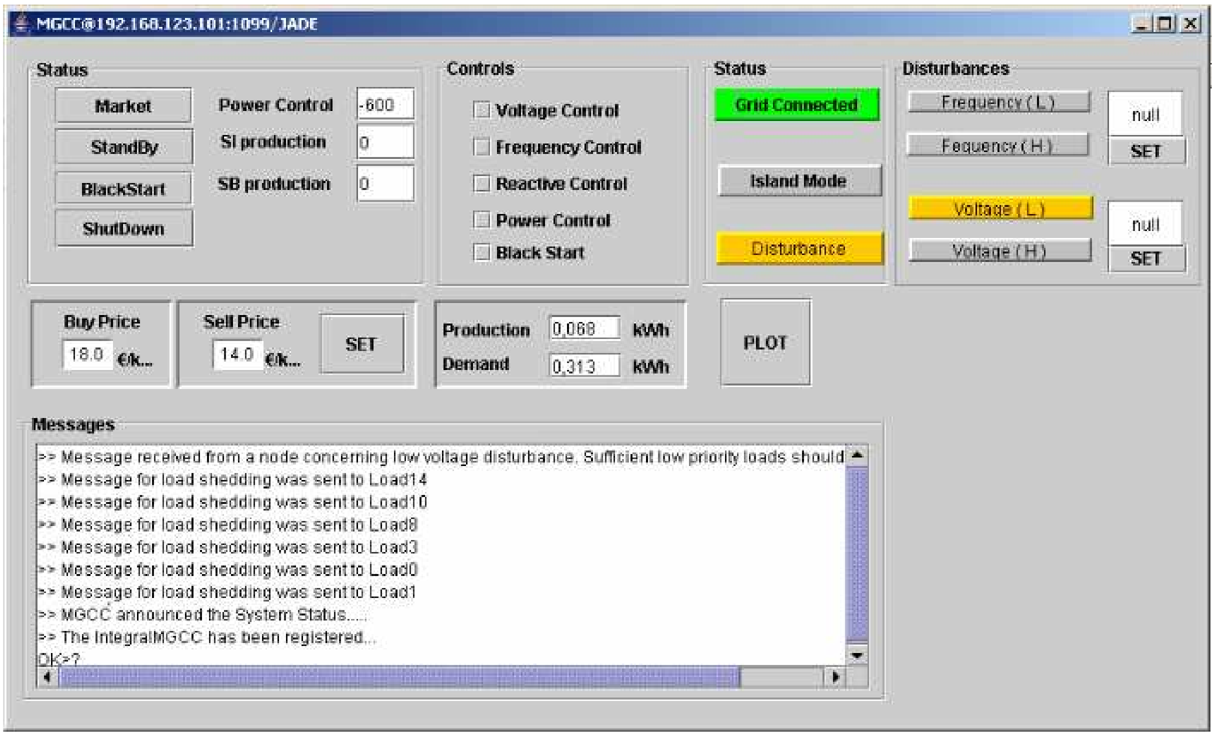
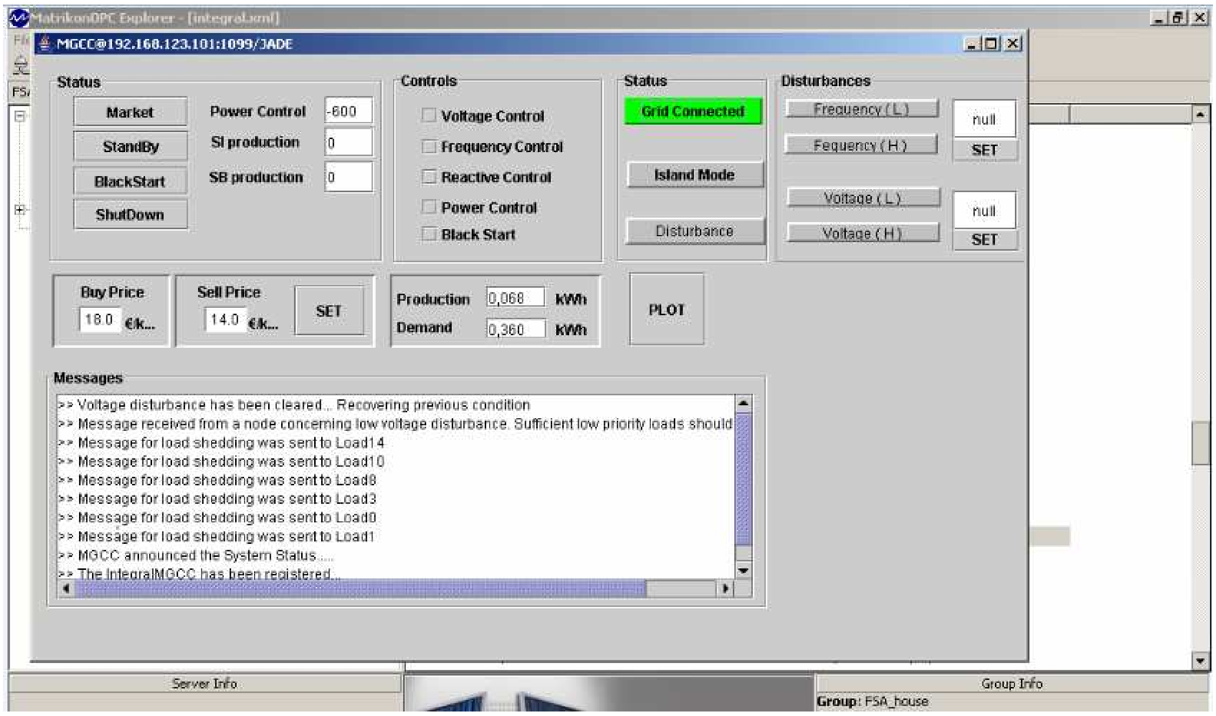


Figure 27 Snapshots of the graphical representation of MGCC agent (Normal operation)



(a)



(b)

Figure 28: Snapshots of the graphical representation of MGCC agent:

Voltage Drop

Recovery Period – Normal Operation

4.3 Evaluation method

As described in Integral deliverable 8.1 [D8.1], the extended ISO9126 standard for software quality was adopted as framework for evaluating the system architecture. An overview of the extended ISO9126 is presented in Figure 2. As mentioned before in Demo A (section 2.1), only some of the quality characteristics will be implemented in software. For the selected characteristics it is indicated how these affect the software architecture.

Main Characteristic	Sub-Characteristic	Motivation
Functionality	Suitability	Is the capability of the system to provide an appropriate set of functions for specified tasks. This is ensured by the task-oriented composition of the multi-agent control system to overcome grid imbalances. Multi- agent control enables the operation of the system under island mode and voltage/frequency disturbance.
	Accuracy	The software product provides complete control of shedding the load for the agreed categories of loads (and appropriate amount of consumption), according to defined priorities set by user, in thecase of grid imbalance, for ensuring that the energy adequacy of the distributed production units is attained.
	Interoperability	The software was developed in Java using Jade framework for integration to achieve easy porting between potential different hosting OS and interoperability. All agents are executed in Jade framework, which is in compliance with the FIPA specifications. The communication between JADE agents adheres to the format specified by the ACL language defined by the FIPA international standard for agent interoperability. The communication between the multi-agent system and the controller software is achieved over Zig-Bee protocol. A DBMS (SQL server) supports the operation of the multi-agent integrated system. This enables the multi-agent control software to gracefully integrate with other load controlling technologies apart from the ones connected over ZigBee and achieve the same results.
	Compliance	In order to achieve compliance open standards have been selected and evaluated so that solution will adhere to. All the agents in the software product were developed according to FIPA specifications, an international standard.
	Security	Security ensures the safe exchange of data without information loss or unauthorized access to this. Security of data transmission is ensured by zigbee protocol design. Hence, communications are secured

		against outsider attacks (e.g. eavesdropping, message injections etc.) while transport infrastructure is accessible only to authenticated nodes. Additionally message integrity, authentication and freshness control of zigbee protocol further secure infrastructure communications.
Reliability	Fault-Tolerance	All the ZigBee nodes should communicate with the central node. The closest nodes to the central one behave as transmitter for the distant ones. If the communication between two successive nodes is lost for any purpose then the ZigBee node communication topology is reconfigured in order to ensure the exchange of the whole information. If the execution of an agent is stopped for any reason the multi-agent system informs the end-user with an error message and continues operating without this agent. When the end-user re-executes the agent, it operates according to the current conditions.
	Recoverability	The software is developed in order to allow operation under critical grid conditions. When the grid recovers, the local system also recovers successfully to the initial state just before the grid imbalance.
	Availability	Network topology design as well as smart routing algorithms and protocols implemented alow for an increased availability of information from nodes. Further more, during the field experiments, all the agents and ZigBee nodes were operating continuously. No information was lost either during ZigBee nodes communication or agent messaging.
Usability	Operability	The whole system setup is automated. After the installation of ZigBee nodes to a plug, it automatically communicates, directly or not, with the central node and acquires a dynamic IP address. The multi-agent system (both JADE platform and the agents) is started simply by running a batch file. On the other hand, The operation of the system can be monitored through graphical user interfaces (GUI), depicting node interconnection, status and measurements.
	Attractivity	The spectrum of functionalities implemented (control, measurements, etc.) as long as the simplicity of operation without affecting the quality of the monitoring, using graphical interfaces makes the software product attractive to users.

Efficiency	Time behaviour	Two time responses should be considered: one for the agent communication and another for the Zig Bee node measurement records. As far as the agent communication is concerned, the agents for controlling the Mas Roig site were executed in the same Jade platform in one PC unit. This minimizes the message transferring delay since there is no need for remote communication between different platforms or PC units, the delay of which depends on various factors (channel bandwidth, amount of transferred information etc). Concerning the ZigBee node measurements, the interval of the records depends on the number of implemented ZigBee nodes and the distance between them, since ZigBee nodes that are closer to the coordinator act as transmitter for the distant ones. In Mas Roig experiments, the load curtailment time response was less than 2,5 seconds. However, in larger scale applications, for example in case of hundreds of agents and ZigBee nodes, the time response might be much higher and thus the control system may become inefficient. In such cases, different control architecture should be implemented, where the system is divided into several autonomous subsystems, which collaborate and are individually controlled by the multi- agent control concept.
	Resource Behaviour	The central ZigBee node was located in a central point in order to be reachable from most of ZigBee nodes. In this way all the nodes could act as real end nodes sending information directly to the coordinator, operating in sleep mode between transmissions and consequently reducing power consumption. However, the fact that some distant resources existed, few nodes were also used as transmitters in order to route information from the distant nodes.
Maintainability	Analysability	The mutli-agent system is able to diagnose for deficiencies though its message reporting system to the central agent controller (MGCC). For example, when an agent becomes unavailable (either due to software / hardware crash or due to link unavailability), the MGCC senses this and informs the user for the lost agent through the graphical interface.
	Changeability	The development of the software was based on object oriented programming principles. This enables the easy upgrade of agents' available functions (named methods) as well as adaptation of existing ones. For example, it is not necessary to equip all the agents with the voltage control function, but only a few, depending on the grid topology each time.

		The priority of the loads can be dynamically changed, according to the user's preferences, by only updating a column in the database. New ZigBee nodes can be dynamically added in order to control additional loads. The new ZigBee nodes will automatically join to the ZigBee community and gracefully integrate with MGCC.
	Testability	When a new function is added it should be validated before it is set in operation in the field. For this reason, off-line simulations should be executed, based on real historical data. The results of the off-line simulations will ensure ezpected operation of the software.
Portability	Adaptability	Jade platform is open source software. All Jade libraries can be downloaded for the official website http://jade.tilab.com and be executed in effectively all operational systems (which can host a java virtual machine). The Leap add-on is also available which allows obtaining a FIPA-compliant agent platform with reduced footprint and compatibility with mobile Java environments down to J2ME-CLDC MIDP 1.0.

4.4 Recommendation for future research

According to the lessons learned from the lesson learned from the implementation within the scope of the Integral project the proposals for future research are:

- Large demonstrations are needed in order to expand the system capabilities and came closer to a commercial solution. The data and the experiences from large demonstration are important in order to optimise the performance of the system considering the constraints from reality. Furthermore extended recordings are needed in order to improve consumer and RES modelling.

- The standardisation is another significant part for future research. As mentioned in the D9.3 several standards (existing or under development) may support the collaboration of the various system. The integration of these standards into the system operation is a critical task.

- The interaction with the customers is important in some cases. In order to provide market functionalities to the system the development of a Web Portal is important. The access through a web application will allow to the customer to configure the system and have the sense that he manages the system behaviour

- Another critical part is the development of Load/RES forecast modules. These functionalities are important for the system development and operation. Current research focuses on the forecasting errors, thus the modules and the subsystem should have the ability to manage this information.

- The system should further enhance the Service Oriented Architecture capabilities in order to support an Integral architecture. The cooperation especially within WP9 revealed that the capabilities of all Demos are important in order to provide a complete system.

5. Evaluation of architecture and infrastructure for Demo C

Concerning the distribution system and its role in the Smart Grids infrastructure, the distribution system of the past is radial and dumb. The distribution system of the future is meshed and intelligent. There are many names being ascribed to a futuristic distribution system, but the dual concepts of meshed and intelligent make Smart Grids the preferred term of the author. There are certainly some proven technologies that will have a role – more or less – in distribution systems moving forward. This includes advanced digital meters, distribution automation, low-cost communication systems, and distributed energy resources. Actually, there are already many demonstration projects showing the promise of these technologies and other ones. This includes the use of broadband communications for distribution applications, closed loop systems using advanced protection, and many using distributed storage and generation. However, these projects tend to use a single technology in isolation, and do not attempt to create an integrated Smart Grid using a variety of technologies.

Major blackouts around the world highlight the need for such a self-healing system for more robust monitoring and control. Emerging power system technologies are also expected to greatly influence operational requirements of power systems. These include dispersed generation, renewable resources, distributed storage and flexible transmission controls.

With all of the Smart Grid research activities; it is mandatory to investigate whether Smart Grid technologies will have any design implications for distribution systems. Will the basic topology and layout of a Smart Grid be similar to what is seen today? Alternatively, will the basic topology and layout of a Smart Grid look different?

Advances in measurement and control technologies offer both challenges and opportunities in dealing with the evolving changes. Equipment with embedded intelligent devices would create opportunities for innovations in sensing, modelling, analysis, simulation, prediction, control, and optimization. This is transforming the mostly electro-mechanically controlled power grid to an electronically controlled one. With latest technologies, such as PMUs (Phasor Measurement Unit), it becomes possible to get synchronized and to ensure the precision measurements required for the realization of the self-healing grid. Modern information technology can provide the backbone for the enhanced computing and communications mandatory to meet the stringent requirements.

In order to realize a self-healing grid, a high performance IT infrastructure will be needed to address gaps in the geographical and temporal coordination of power system monitoring and control. Current practices require considerable improvements at various hierarchical levels, including substations, control areas, regions and the grid. Temporal coordination will require improvements in adapting the faster and often local controls to the slower global controls. But what are the real performances desired from the IT infrastructure?

Environmental and economic sustainability are essential variables in the 21st century's energy equation. But existing infrastructures and systems lack the flexibility to evolve to meet higher demands for efficiency and reliability. The Smart Grid will return balance to this "cost-benefit" paradigm by introducing intelligent response into the interaction between supply availability and demand. With the help of markets and real-time system information, utilities will be able to work together with consumers to produce the most cost-effective and efficient supply mix.

Many of the current research and development activities related to Smart Grids share a common vision to desired functionalities. Technology should not be used for its own sake, but to enhance the ability of the distribution system to address the changing needs of utilities and their customers. Some of these desired functionalities include:

- Self-healing;
- High reliability and power quality;
- Resistant to cyber attacks;
- Wide variety of distributed generation and storage options;
- Asset use optimization;
- Minimization of operations and maintenance expenses.

Demo C was focused on emergency operating conditions, showing self-healing capabilities of DER/RES aggregations. The aim of this demo was to provide solutions to reduce outage time and operation costs, due to a fault occurrence within the network.

One of the new emerging ideas to protect the electric power system against catastrophic failure is the use of self-healing approaches (SHA). The objective of these advanced approaches consists consecutively in detecting, localizing and isolating the fault before supplying again the maximum of consumers, who were affected by the disturbance. Once it is determined that a wide area of the system has been perturbed, SHA breaks up the system into small parts to reduce the effects of the fault occurrence by limiting them to the smallest part. The sane parts of the network can be supplied again, improving the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). The entire system could therefore be restored after the disturbance has been eliminated. The speed of reaction has a large impact on the quality of service to the customers.

However, fault location in distribution networks is always complex, due to:

- non-homogeneity and uncertainties on line parameters that are mandatory for the fault location algorithms,
- fault impedance ignorance which can even vary during the fault,
- load and generation uncertainties,
- imbalance of certain faults which are not included in the regular fault location methods and are modified by the source interconnections,
- neutral grounding impedance which influence the phase to ground (most encountered – from 60 to 80% of permanent faults) fault currents and leads to use transient signal analysis.

The fact that a feeder has many branches, adds a major difficulty in locating the fault although the fault distance from a substation could be evaluated. In order to determine exactly the faulty section when a fault occurs in distribution network with or without DER, an interesting approach, which combines fault indicators (FI) states with fault distance computation, has been developed.

In general, SHA is expected to include the three following high level functions:

- fault distance computation,
- fault location and isolation by combination of FI states with fault distance computation,
- fault isolation and service restoration.

5.1 Problem statement

The demonstration C aims to deal with the self-healing ability of the distribution network when important disturbances (such as short-circuit) occur. The point is how to quickly locate a faulty section, then eliminate it and automatically restore the normal service for the sane part of the network. Before handing the detail functionalities needed for this purpose, the characteristics of distribution network and the state of the art of short-circuit will be addressed in the following section.

5.1.1 Constitution of distribution network

In distribution networks, we can distinguish two types of network, according to the conductors: Overhead lines and Undergrounds cables.
The overhead installations consist of three wires, three-phases or four wires, three-phase plus neutral, depending on whether the neutral is distributed or not. These kinds of installation are suitable in weak load density areas, for instance: small towns or villages. The underground installations are usually specified for strong load density areas, with environmental and safety constraints such as sub-urban or crowded cities. They consist of generally three-phase cables with synthetic or polymer insulator.
The comparison of these two types of installation in several countries is presented in the following table:

Country	France	Great-Britain	Germany	The Netherlands	Japan
Overhead (%)	82	56	44	0	97
Underground (%)	18	44	56	100	3

Table 5-1. Types of distribution network in several countries

There are several configurations of distribution network but most distribution circuits operate in radial configuration.

5.1.2 Neutral grounding mode for distribution network

The fault current (when connected to the earth) depends strongly on the grounding mode of the neutral potential of the transformer at the (HV/MV) substation. The following figure provides the mostly used neutral grounding in European countries.

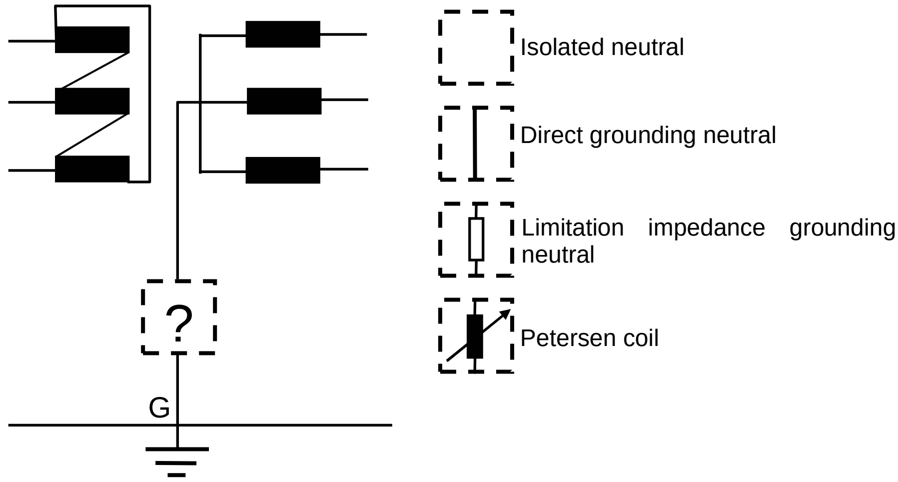


Figure 29: Grounding neutral mode

Each type of grounding neutral has its particular characteristics, which are chosen according to the specific application. In France, major part of the grounding of rural systems is carried out by limitation impedance. Ii is slowly replaced by compensated grounding. In the following table, the grounding neutral mode of several countries is presented:

Grounding neutral	Austria	Belgium	Switzerland	Germany	France	Italy	Portugal	Finland	Spain
Isolated	**Yes**	**Yes**	**Yes**	**No**	**No**	**Yes**	**No**	**Yes**	**No**
Direct	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**Yes**
Impedance	**No**	**Yes**	**No**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
Compensated	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**In study**	**No**	**Yes**	**No**

Table 5-2. Grounding neutral mode in certain European countries

5.1.3 Origins and type of short circuit in distribution network

- For overhead installation: the overhead lines are very sensitive to the environment due to the height from the ground, the distance between phase lines and the insulators. So, principal fault sources on the distribution lines consist of: atmospheric aggressions as lightning and storm -45%; falls of trees - 18%; failures of the materials – 13%.
- For underground installation: they are naturally protected against atmospheric aggressions, but make them invisibles to the nearby works. The main origins of the fault are thus: nearby work on the ground – 30% and failures of materials -30%.

Usual short circuits in distribution network can be divided into many kinds according either to the physical phenomena of fault or to the duration of fault.

According to the physical phenomena of fault, it can be distinguished:
- single-phase short-circuit: a phase directly or indirectly in contact with the ground
- two-phase short-circuit: two phases in contact between themselves, with or without grounding

- three-phases short-circuit: three phases in contact between themselves, with or without grounding, even if this grounding have no impacts if the circuits are balanced

According to the duration of the fault, there are:

- transient faults (70% - French figures): which can be cleared shortly, due to the swinging of lines or a branches of trees under the effect of a strong wind. In function of fault duration, it is able to subdivide into different types: intermittent fault, semi-permanent and auto-extinguisher fault. These cases usually occur on the overhead lines.
- permanent fault (30% - French figures): due to serious injuries of the insulators. It is practically always the case for underground cable short-circuits.

Depending on the type and the characteristics of distribution network and the fault as well, system operator decide the suitable functionalities described in D2.1 and D2.2 of the INTEGRAL project for fault location and restoration service. The followings tables present actual default statistics of the fault and the loss of energy time used by French distribution network operator and planning engineer:

Fault characteristics		**Occurrence/100km/year**	
		Overhead	**Underground**
Permanent fault		5	4
Transient fault	**Very short (< 30 s))**	70	
	Short (< 3 min)	27	

Table 5-3. Fault statistics

Action	**Duration time (minutes)**
Remotely restoration time	3
Manual restoration time	60
Re-supply by diesel generator	240
Duration of a overhead section cut-out	300
Duration of a twist section cut-out	600
Duration of a underground section cut-out	960

Table 5-4. Restoration time statistics

From the statement above (average remotely restoration time), the reliability of the distribution network could be enhanced by using self-healing agents and related components. Particularly, at the actual regulation context and with the high penetration of DER/RES expected, the security constraints may become more and more restrained. Nevertheless, the artificial intelligent along with the development of ICT system as well as ADA devices should be able to resolve this problem. Indeed, that is the purpose of the demonstration C of Integral project developed in Grenoble, France, to deal with the fast self-healing distribution network in presence of DER/RES.

5.2 Scenarios definitions

Several use cases have designed in order to test all the situations that can be encountered in the real life. The focus will be made on the reliability of the proposed actions sent to the SCADA by the agent in charge of the fault location and isolation process. Several items (use cases as defined in D4.4 of the INTEGRAL project) have been tested:

- Robutness versus fault location;
- Robutness versus fault type;

- Impact of communication performances;
- Robustness versus the grounding mode;
- Impact of the power flow inside the network before the fault;
- Impact of the initial topology (added in the project after the D4.4 deliverable).

5.3 Self-healing conception

The demonstration C handles with self-healing ability for a distribution network which includes overhead network for one part and underground network for another part. The faults targeted for this demonstration are short-circuits which often take place in distribution network. The short-circuit may be either asymmetric (like single or two phases short-circuit) or symmetric (three phases short-circuit). Otherwise, the short-circuit may be characterized by existence duration: permanent (often on underground network) or transient (often on overhead network) with also by different neutral grounding modes. The demonstration is expected to deal with every aspect of short-circuit in distribution network.
The principal objective of the demonstration C is to deal with the short-circuits occurring in distribution and find out how the affected system could be identified and restored in the shortest duration with help of ICT system as well as the available ADA devices.

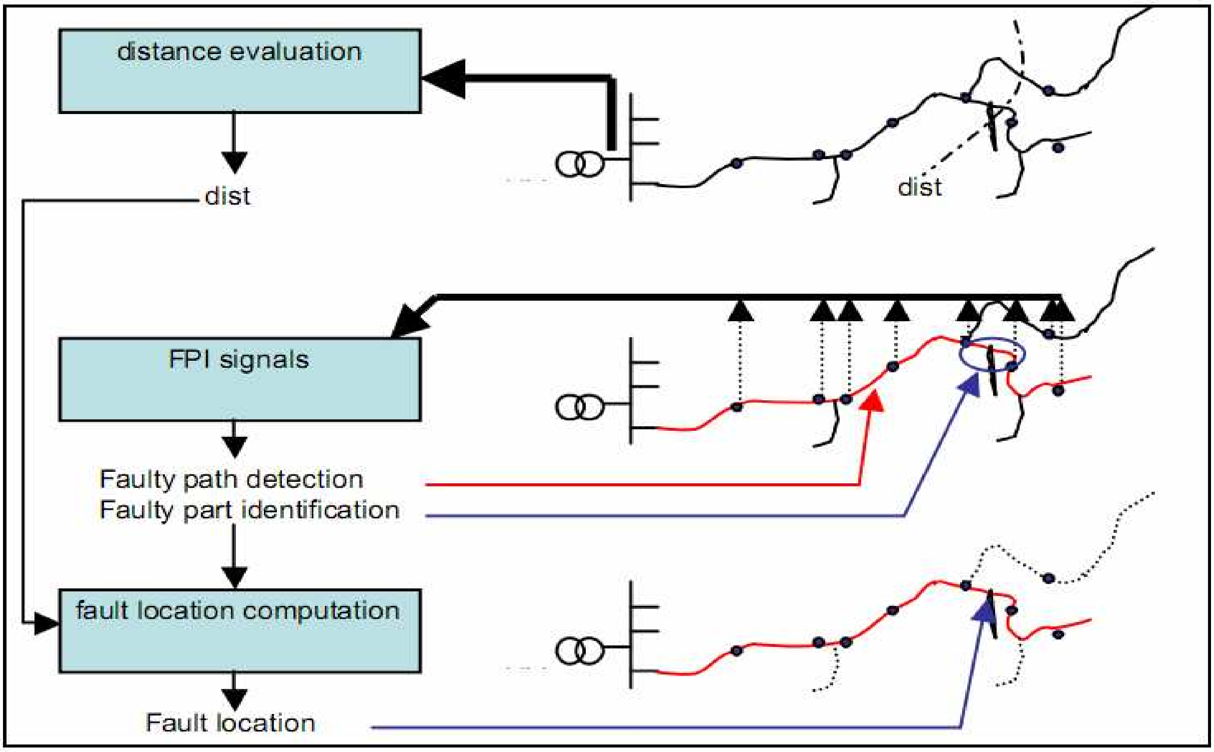


Figure 30: Fault location process

In fault condition in distribution network, the current increases and the voltage decreases. The purpose of the test is to monitor the real-time behaviours of current and voltage in order to assure the good communication when the whole demonstrator launch. Therefore, the current behavior is realized by modifying the value of load whereas the behaviour of voltage is done with an auto-transformer. The following figures show the real-time behaviours of current and voltage when the MATLAB program is running. Once the data values change, the client toolbox obtains the changed value and logs them for the forthcoming treatment.

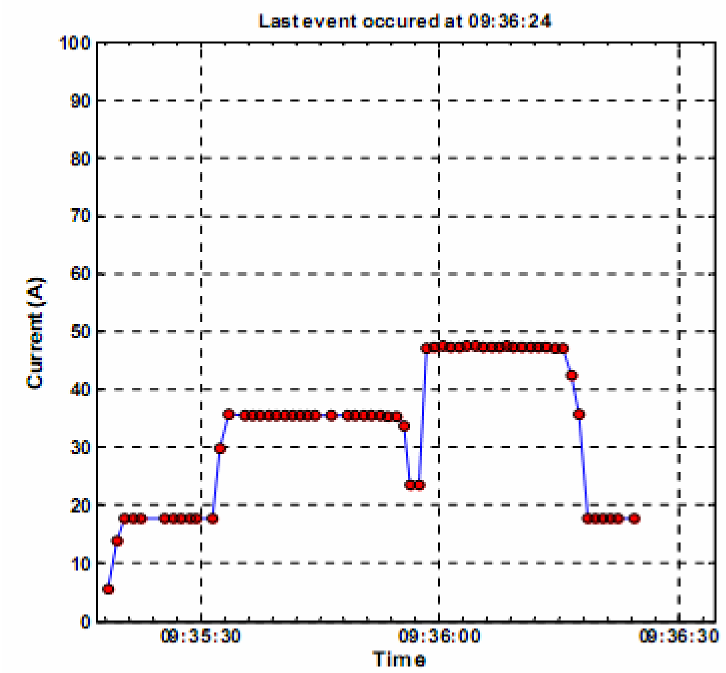


Figure 31. Real-time behaviors of phase current

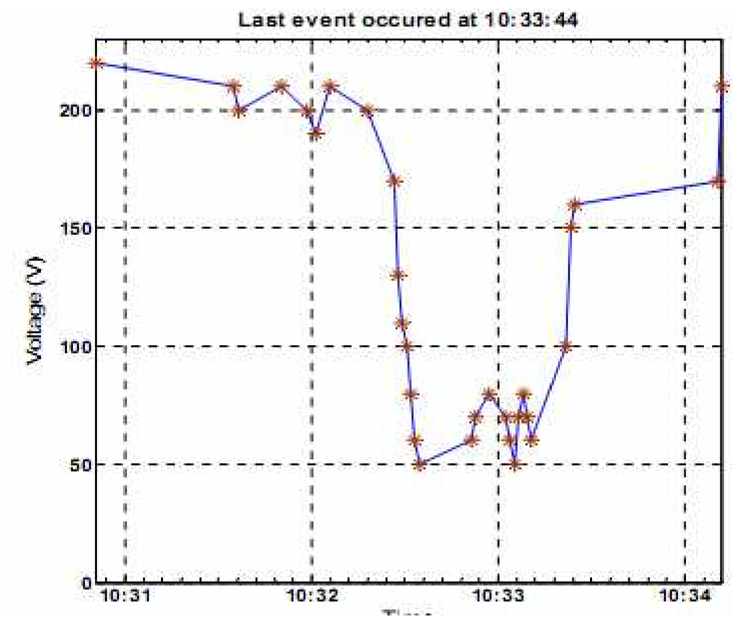


Figure 32. Real-time behaviors of voltage

These previous curves show only the Root Mean Square value of the current and voltage which was not relevant for our test bench. Indeed, as we desired to be able to cope with compensated grounding, a 5 kHz recording was developed with LabView and an associated OPC Toolbox.

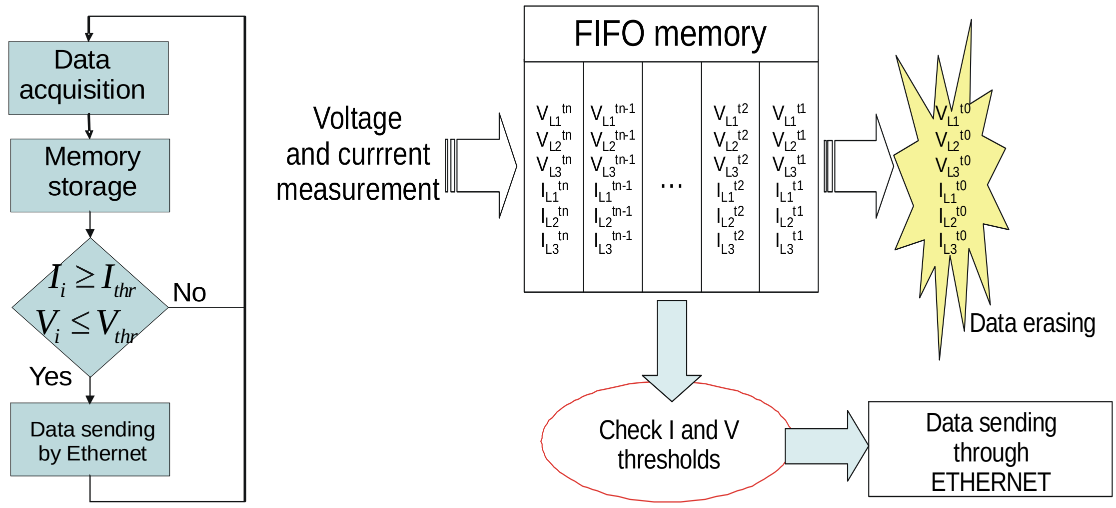


Figure 33. Data recording (left) and principle of recording to the memory of the disturbance recorder (right)

The previous figure is showing the implementation of the fault recorder to be able to give the pre fault and the faulty currents/voltages to the agent for further analysis.

5.4 Test bench

The demonstration C aims to deal with the self-healing ability of the distribution network when important disturbances (such as short-circuit) occur. The point is how to quickly locate a faulty section, then eliminate it and automatically restore the normal service.

A µnetwork which is a reduced dimension of a real distribution network (EDF) with a reduction ratio is implemented in Electrical Laboratory of Grenoble. Every electrical element, like distribution lines, transformers, generator, load, asynchronous machine, are real but with a reduced dimension in order to function in 400V experimental level instead of 20kV level.
Almost of the operation states of this network would be observed and communicated thanks to the measurable package on each element or via the communicant devices. The information from many IEDs implemented in the system, issued when a short-circuit occurs, such as FPI (Fault Passage Indicator) or RTU (Remote Terminal Unit) or FR (Fault Recorder), will be gathered to several server called local agent. This information allows operator to achieve the high level functionalities in order to quickly deal with the fault. The signals used for self-healing functionalities are fault current, voltage in time value and RMS value and states of remote control switches as well.
To completely fulfil these requirements, an ICT platform will be implemented in situ and respect the IEEE/IEC standard or some specific industrial standard.

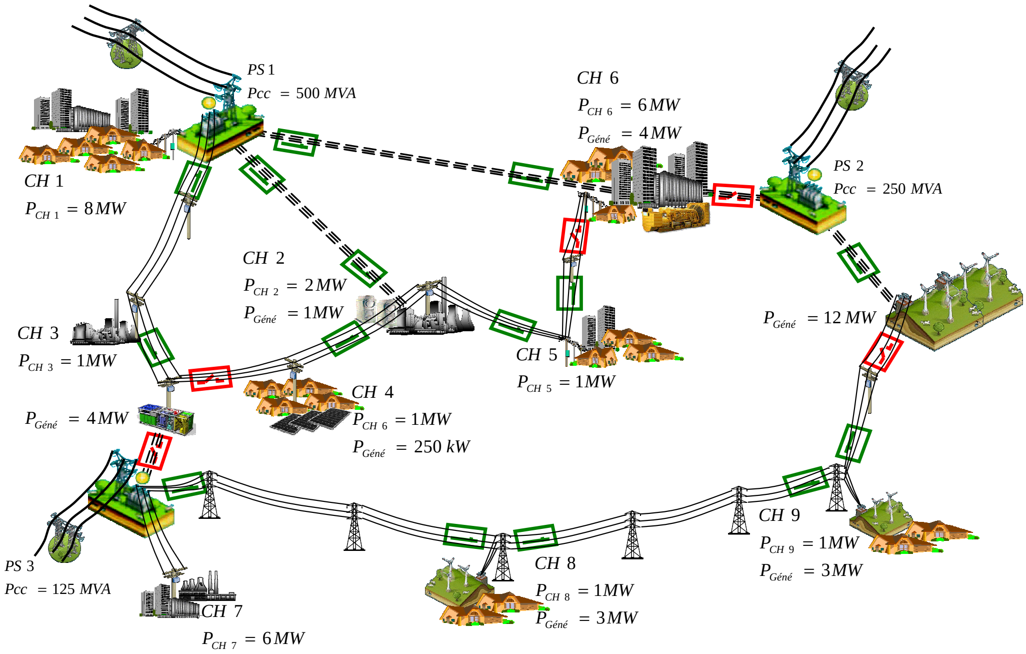


Figure 34: Topology of the real French EDF distribution feeders from three different substations (PS)

In order to represent the behavior of the real network during a fault (overload done with a fault resistance), as shown in the figure 34, and satisfy economical conditions, a test bench network of 30kVA, 0.4kV was adopted (power ratio 1:1000 and voltage ratio 1:50). It includes 18 lines (emulated with RL impedance characteristics plus remotely controlled switches), 14 nodes, 9 loads (emulated by induction machines or dimmers), 5 sources (emulated by synchronous generators). The scaling of the system was respected both on static and on dynamic behaviors. This analogical emulation allows to test real RTUs (Remote Terminal Units) fed by real fault (overloads) currents and voltages.

A real Supervisory Control and Data Acquisition (SCADA) has been developed (under industrial software named PCVue) to validate the Agent-SCADA interactions. It is linked with Programmable Automation Controllers (PACs, one in every substation for substation control/protective relay emulation plus an additional one for surrounding load and source control). Figure 35 presents the SCADA interface.

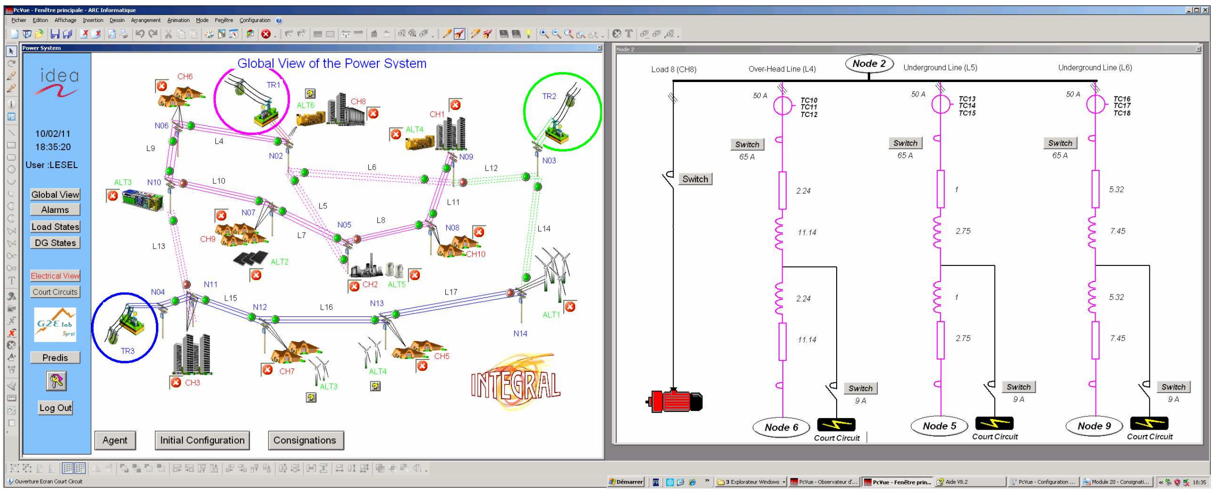


Figure 35: Developed SCADA interface to emulate the DNO actor

To be able to evaluate the ICT performances requested by the self healing agent, different layers of communication (RTU to SCADA/intra substation/PAC to SCADA/RTU to agent to SCADA) and associated monitoring were developed. The figure 36 presents the ICT structure of the INTEGRAL demo C test bench. The communications needed for the self healing process are controlled completely by an emulated ICT system (based on TCP IP). This network (Level 1 in figure 4.9) is able to control bandwidth, latency and even error rates but also analyzing (in off line mode) all the protocols used between RTUS, agent and SCADA during a fault. The level 2 is presenting the different RTUs (real communicating fault passage indicator, fault recorders) a distributed database, the agent and the SCADA server. The level 3 is presenting the PACs and other controllers of the test bench.

The fault passage indicators (FIs) are one of the keys elements of the architecture of the Demo C. They are micro-processor based measurement devices, including various interface units to communicate with both the SCADA and the local agent. This is real RTUs from a well-known electrical manufacturer, Schneider Electric Telecontrol.

The fault recorders (FRs) were completely developed during the INTEGRAL project, allowing various grounding of the substation, such as compensated earthing as Petersen Coil. These particular grounding are reducing/removing the fundamental frequency of the fault current. Indeed, this coil is adjusted on the capacitance of the lines and acts as a filter. To be able to asses the distance to the fault, a medium frequency evaluation in the transient phase can find the correct distance to the fault. Indeed, a 5 kHz recording to every currents and voltages in the substation is done and these records are downloaded by the agent for this distance computation.

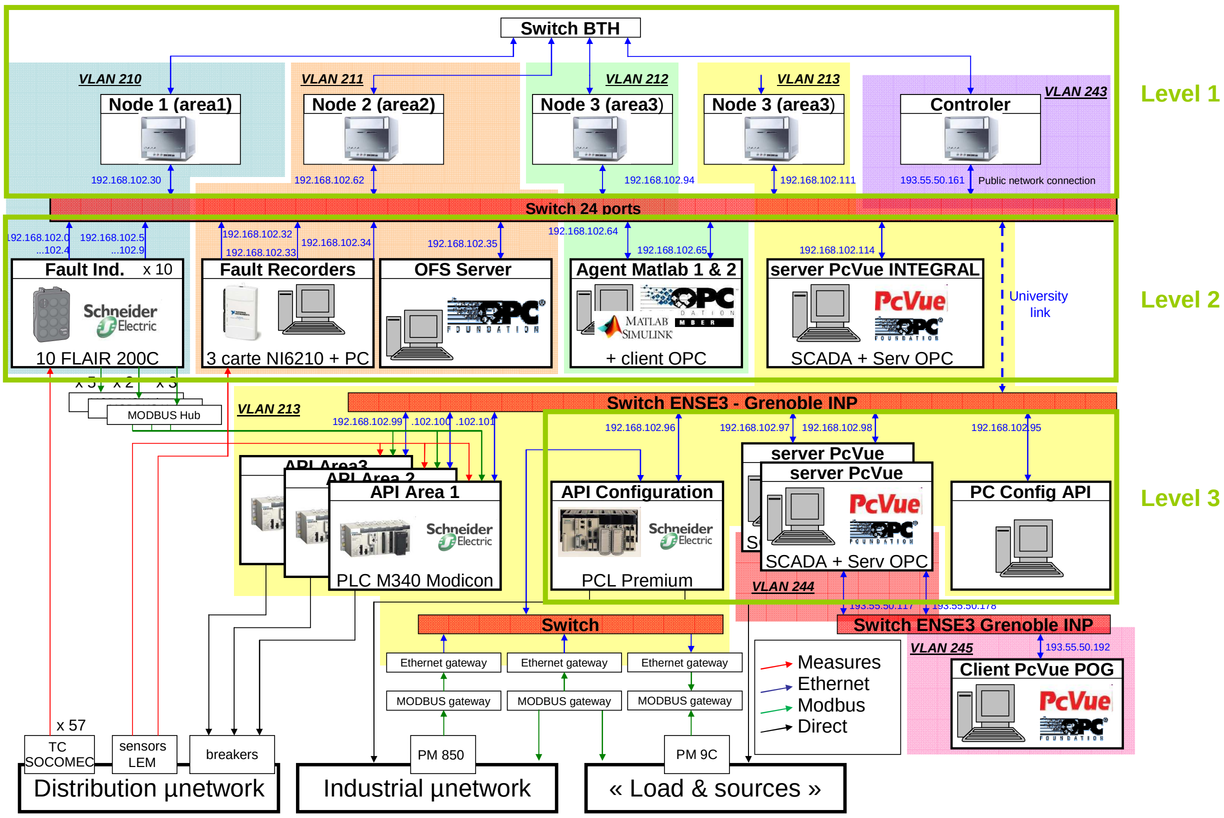


Figure 36: Developed ICT infrastructure to asses the communication performances

5.5 Major results

The agent has shown, during the different scenarios, a good robustness and a high adaptability to the network states.

The test bench was also developed to be able to test various ADA functions and their interactions with both IT infrastructure and real RTUs as shown in Figure 37.

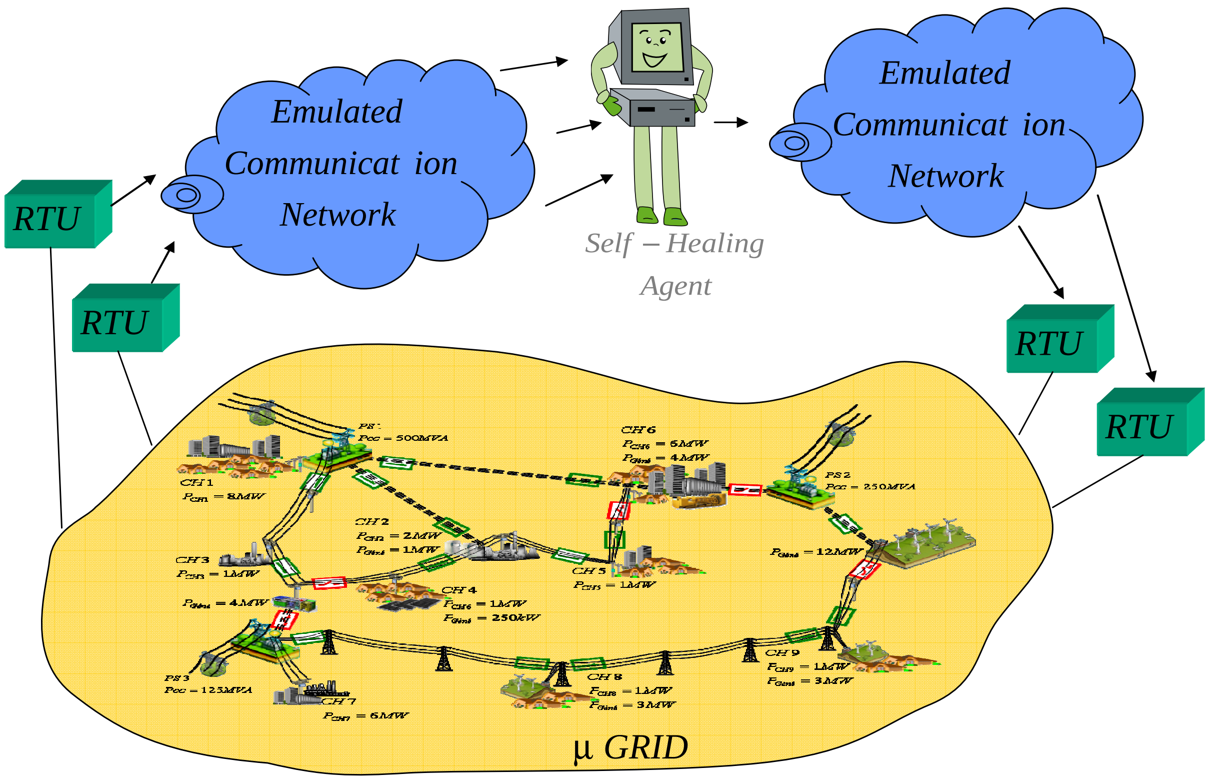


Figure 37: Agent in the loop test bench with both real RTUs and emulated IT infrastructure

The tested scenarios are modifications on:

- fault location (seven lines can handle overloads in the distribution network),
- grounding of the substation (both resistive and impedance grounding are available),
- type of the fault (single phase, two phase, two phase to ground and three phase faults),
- communication network performances (latency, error rate and bandwidth),
- power flow inside the network (loads and sources),
- topology of the network before the fault (normally open point location in loopable structures).

Figure 38 presents the IT emulation and the results extracted from the different IT nodes able to monitor and modify the IT performances.

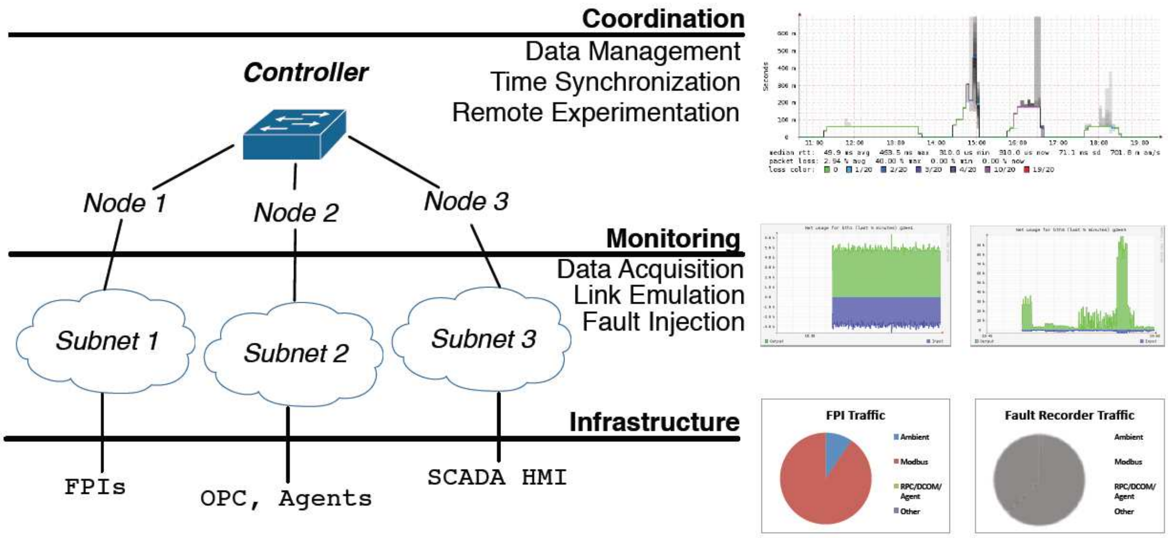
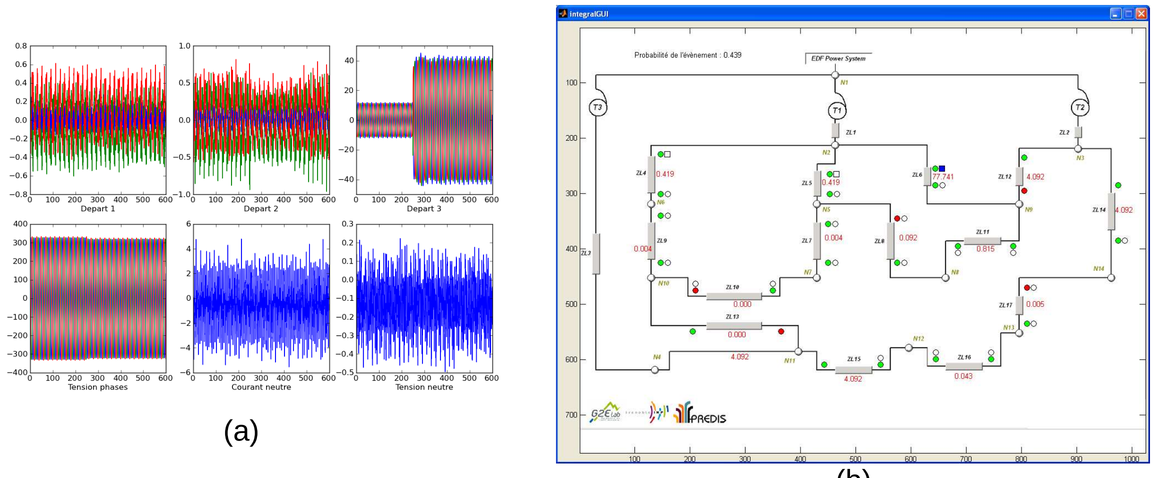


Figure 38: Snapshots of the monitoring present in the demonstrator

All the different scenarios show the very good performance and robustness of the self healing agent. Figure 39(a) shows the data recorded in the FR of substation 1. Figure 39(b) shows the answer from the Agent, indicating the probability of fault occurrence in every lines of the distribution network.



(a) (b)

Figure 39: Fault recording (a) and Agent GUI (b)

5.6 Evaluation method

As described in Integral deliverable 8.1 [D8.1], the extended ISO9126 standard for software quality was adopted as framework for evaluating the system architecture. An overview of the extended ISO9126 is presented in Figure 2. As mentioned before in Demo A (section 2.1), only some of the quality characteristics will be implemented in software. For the selected characteristics, it is indicated how these affect the software architecture.

Main Characteristic	Sub-Characteristic	Motivation
Functionality	Suitability	Is the capability of the system to provide an appropriate set of functions for specified tasks. This is ensured by the task-oriented composition of the multi-agent control system to locate, isolate and reconfigure the distribution network.
	Accuracy	The software product provides complete control network components to react to a fault such as a short circuit.
	Interoperability	The software was developed in Matlab with OPC standardized interaction with all the real grid components such as Fault Passage Indicators through a dedicated distributed database and the Fault recorders through OPC server build in solution.
	Compliance	In order to achieve compliance open standards have been selected and evaluated so that solution will adhere to.
	Security	Security ensures the safe exchange of data without information loss or unauthorized access to this. The test bench was realized to be able to test various malicious attacks and to test the security and integrity of data. In that sense, this test bench offer many possibilities for enhancement in security in the future Smart Grids.
Reliability	Fault-Tolerance	If the communication with any real devices is stopped for any reason the multi-agent system informs the end-user with an error message.
	Recoverability	The software is developed in order to allow operation under critical grid conditions. When the grid recovers, the local system also recovers successfully to the initial state modulus the grid reconfiguration.
	Availability	Network topology design as well as smart routing algorithms and protocols implemented allow for an increased availability of information from nodes.
Usability	Operability	The whole system setup is not automated. There is not automatic plug and play implementation in the Demo C feature.
	Attractivity	The spectrum of functionalities implemented (control, measurements, etc.) as long as the simplicity of operation without affecting the quality of the monitoring, using graphical interfaces makes the software product attractive to DNOs
Efficiency	Time behaviour	The Demo C implementation is perfectible. The very idea was to be able to test any kind of ADA function, starting from the self healing one. Tests on the IT performances have shown great interdependence between self healing function performance and IT

		latency. Results from 8 seconds to more than 40 seconds (with basic internet) can be achieved. On this aspect, Demo C has given interesting inputs in the Smart Grid distributed control implementation with a bottom up approach.
Maintainability	Analysability	The multi-agent system is able to diagnose for deficiencies though its message reporting system to the central self healing agent. For example, when any RTUs become unavailable (either due to software / hardware crash or due to link unavailability), the agent senses this, informs the user for the lost agent through the graphical interface and when a fault is occurring, is computing the most probable fault location.
	Changeability	The development of the software was based on object oriented programming principles. This enables the easy upgrade of agents' available functions (named methods) as well as adaptation of existing ones.
	Testability	When a new function is added it should be validated before it is set in operation in the field. For this reason, off-line simulations should be executed, based on real historical data.
Portability	Adaptability	Matlab is one of the most used scientific software over the world. Its interpreted code allows any engineer to easily understand the source code.

5.7 Recommendation for future research

New challenges arise after the various scenarios tested during Demo C.

- Large demonstrations are needed in order to expand the system capabilities and came closer to a commercial solution. The data and the experiences from large demonstration are important in order to optimise the performance of the system considering the constraints from reality.

- The standardisation is another significant part for future research. As mentioned in the D9.3 several standards (existing or under development) may support the collaboration of the various system. The integration of these standards into the system operation is a critical task. This should allow the IT performance requirement homogenous and thus reduce the costs.

- The interaction with the customers is important in some cases. Indeed, on some very specific cases (line overloads), the agent should not be able to reconfigure and re-energize all the customers without power modulation for some of them.

- The system should further enhance the Service Oriented Architecture capabilities in order to support an Integral architecture. The cooperation especially within WP9 revealed that the capabilities of all Demos are important in order to provide a complete system.

- As majors concerns for low impedance fault (short circuit and not very large overloads as designed in the test bench), reaction of synchronous generators as combined heat and power could modify the short-circuit currents and might impose evolution in the fault passage indicators (FPIs) such as directionality that can be sent to the Agent.

- Master to master protocols should also be preferred to increase the performances of the agents distributed into the SmartGrids.

- While having too few information from the FPIs (not running or experiencing a bad link), multiple point fault recorders could increase the accuracy of the fault position evaluation and increase the probability to successfully locate the faulty part of the network.

6. The integrated control concept

The multi-agent control concept has been proved in the three demos as described in the previous paragraphs. However, the multi-agent setup at these sites was completely different. Therefore the partners have evaluated all results and issued a public report (see deliverable D8.2). Based on these experiences, the partners developed a general ICT architecture of a system that enables scenarios as have been executed during the three Integral demos. See therefore public deliverable D9.2. Furthermore, DER/RES reference information model has been described in public deliverable D9.3 and the IDC agent software functional and technical specification has been given in public deliverable D9.4.
With this information industry should be capable to design and apply integrated multi-agent control concepts.

7. Evaluation of the Integral architecture

The WP9 provided the recommendations for the Integral Architecture. The work started by analysing the various business cases and the common actions required between the various demos. Figure 40 illustrates these interactions.

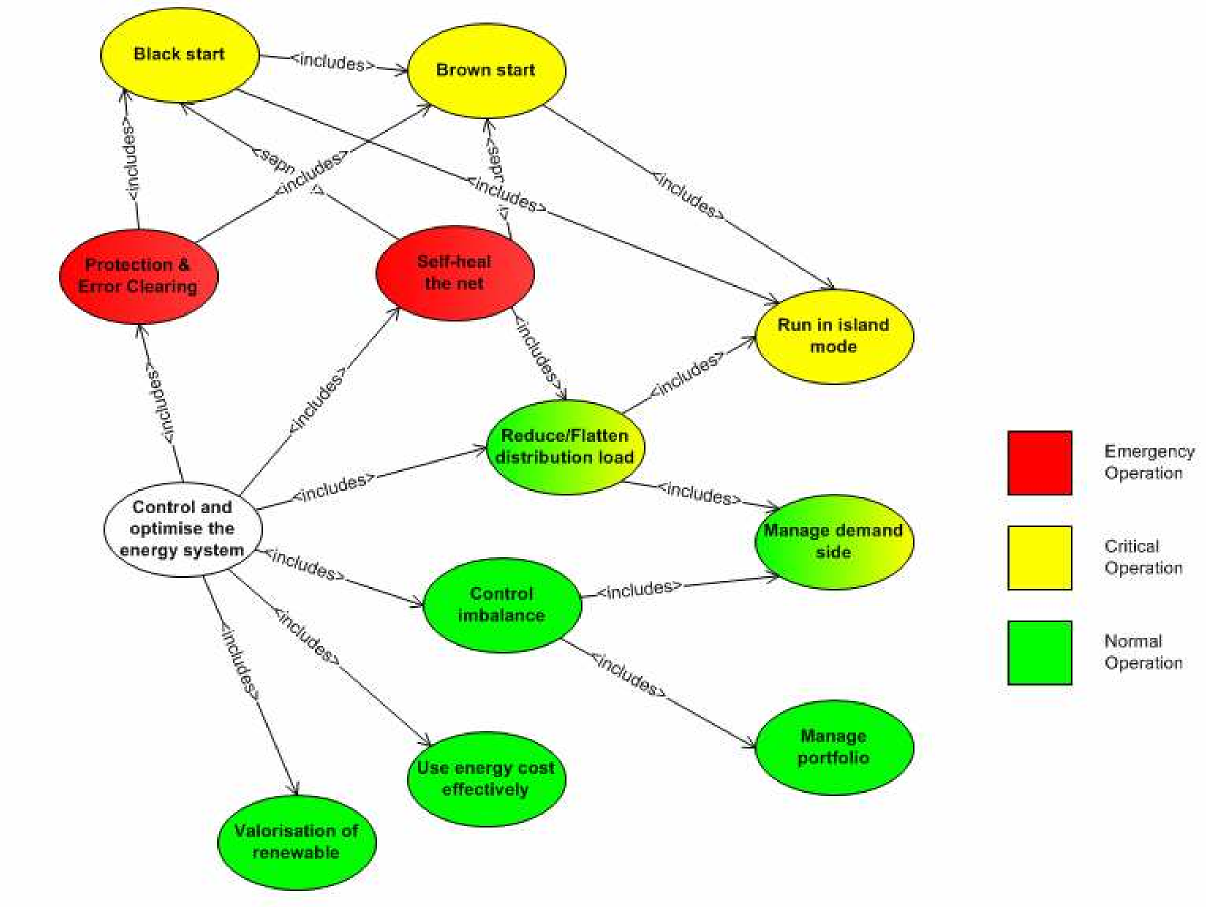


Figure 40: Use Cases of Integral System

Next in D9.2 the various views of the system have been presented. An architectural model consists of a number of views. Each view focuses on one aspect of the system or software. Together these views make up the architecture.

A common approach for describing software architecture is the 4+1 view method [4+1]. The software architecture is described in 5 views.

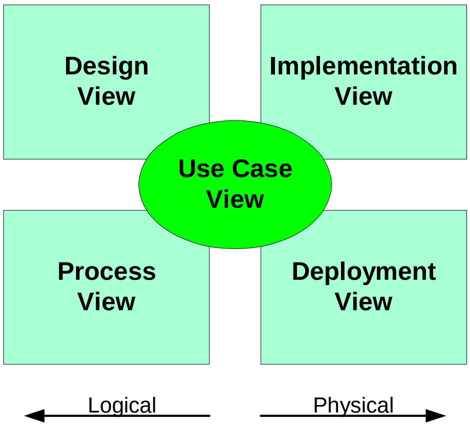


Figure 41 The 4+1 view method

Next in D9.3 a proposal for the implementation of such a system has been provided (Figure 42) by defining a set of (Web) services that will allow the interaction between the Demos. Figure 43 presents the usage of the Services defined in D9.3 in order to coordinate the three demos in order to black start the system.

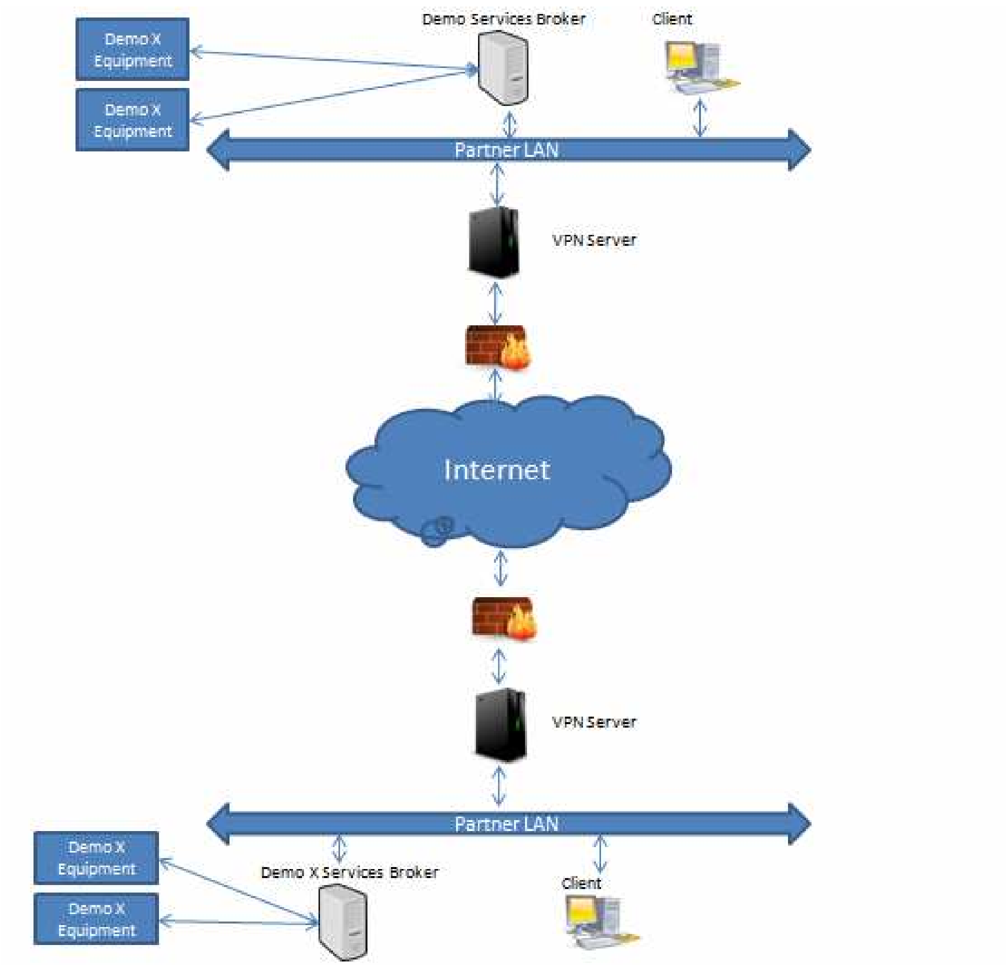


Figure 42 Overview of the data exchange architecture

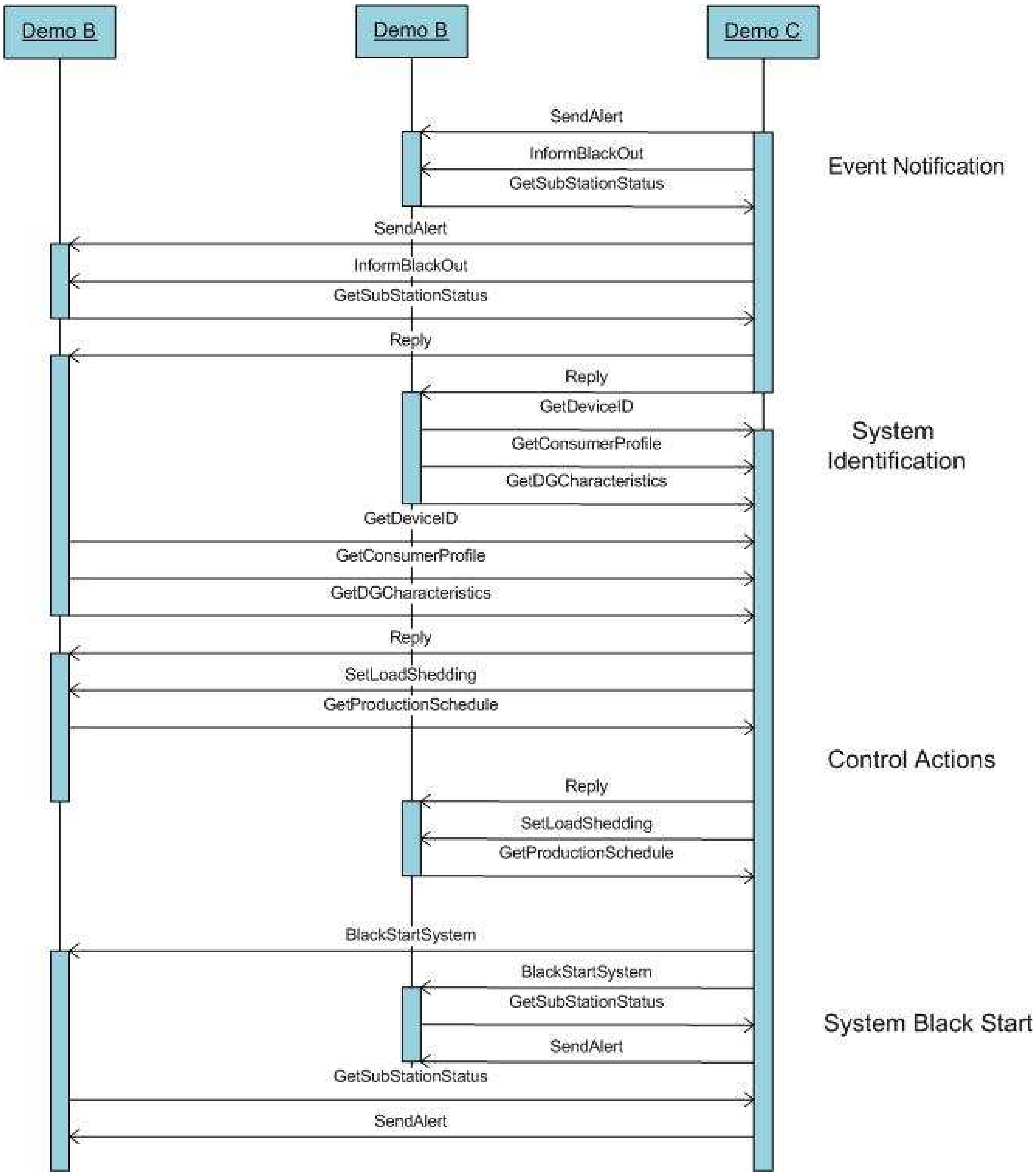


Figure 43 Interactions between the demos in case of Black Start

Since the system has not been implemented the evaluation will focus on suggestions for future research. More specific the experience gained through the design of the common architecture showed that the following topics should be issued:

- The ICT security is the primary concern. All future solutions should consider the security problems. Especially in large integrated systems as the one proposed by the Integral Consortium, one weak point could cause problems to the whole system.

- Demonstrations are needed in order to expand the system capabilities and came closer to a real solution. The data and the experiences from demonstration are important in order to build the system.

- The system should further enhance the Service Oriented Architecture capabilities in order to support an Integral architecture. WP 9 provided a roadmap towards this approach. Definitely this approach is most appropriate regardless the way it will be implemented.

- The standardisation is another significant part for future research. As mentioned in the D9.3 several standards (existing or under development) may support the collaboration of the various system. The participation in standardisation bodies is critical in order to adapt accordingly the system.

- Another critical part as mentioned previously is the development of Load/RES forecast modules. These functionalities are important for the system development and operation. Current research focuses on the forecasting errors, thus the modules and the subsystem should have the ability to manage this information.