INTEGRAL

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

Deliverable D8.1

Definition of test and evaluation procedures

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Acronyms and Abbreviations

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
IEA	International Energy Agency
JADE	Java Agent Development Environment
LAN	Local Area Network
LV	Low Voltage
MAS	Multi-Agent System
MG	Micro-grid
MGCC	Micro-grid Central Controller
MTBF	Mean Time Between Failure
MV	Medium Voltage
OLE	Object Linking and Embedding
OPC	OLE for process control
PCC	Point of Common Coupling

PCCN	Protection and Numeric Control Command
PES	Power Electronics System
PM	Power Matcher
PRP	Programme Responsible Party
PV	Photo-Voltaic
RES	Renewable Energy Sources
SOC	State-Of-Charge
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol

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 are detailed as a previous study in the different D2.x and D4.x deliverables.
The scope of this deliverable is to present the evaluation procedure of the Demo Sites. The evaluation procedure includes two parts: the evaluation of the ICT performance as well the electrical performance. Taking into account that the core of the project is 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. Another critical issue is to evaluate the advantages offered by this technology over the traditional control approaches.
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.

1. Introduction

The scope of this deliverable is to present the 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. Another critical issue is to evaluate the advantages offered by this technology over the traditional control approaches.

Furthermore, the evaluation should provide a solid indication of what should be done in future research projects in the area of distributed control in power systems and in DER control in particular. This evaluation should therefore not only examine whether the installations in the test sites meet their specifications, but mainly to define further needs and problems to be solved. Therefore, it is critical to have a detailed description of the technical solutions adopted in the various sites.

This deliverable will be 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. Definition of test and evaluation of 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). The test configuration is given in Figure 2-1. A top-level Auctioneer aggregates three sub-clusters: one from a residential area with electricity producing or consuming heating systems in homes, one connected to test-facilities at ECN and one connected to Gasunie facilities.

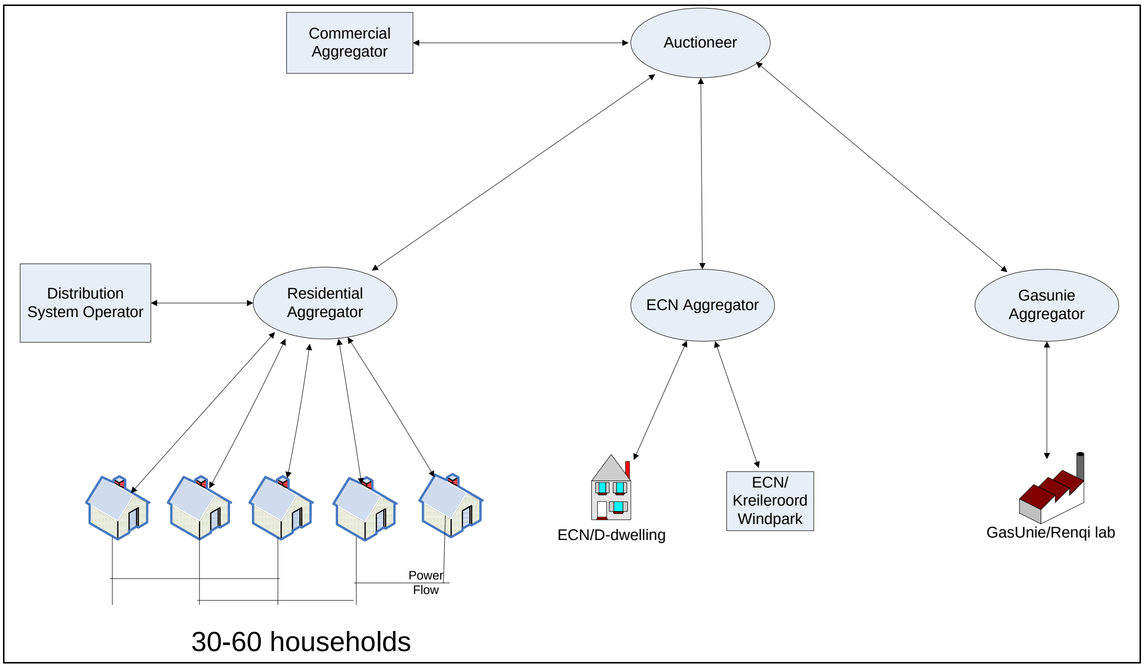

Figure 2-1 Experiment A configuration

2.2 Evaluation of the system operation

For the system, a number of use cases (applications) have been defined (see D5.1a of this project for detailed use case descriptions). Because operation of the devices strongly depends on the heat demand and the production of renewable resources like solar energy and wind, the field test will be conducted to cover summer and winter as well as autumn and spring. For the final use case implementation, there is an incremental development trajectory. The following discussion concerns evaluation of operation of the final system. The evaluation will be done per use case. The data required should enable analysis of the primary process status to bid curve translation by the device nodes. They should aid to the analysis of the agent behaviour. Furthermore, analysis of the aims of the use cases should be possible. To that end, detailed measurements of power and energy streams per device are necessary. The current measurement configuration also allows using parts of the network having data base values for reference, and other parts being physically connected.

Requested signals, as should appear in the database, for all use cases, necessary for primary processes and the PowerMatcher market evaluation, are the following:
Per node (time dependent) : $P^{1}_{el}(t)$, $P_{el,alloc}(t)$, $P_{th}(t)$, $E^{2}_{el}(t)$, $Q_{th}(t)$,T^{3}_{sp}, $T_{outside}$ $T_{realized}$, $SOC^{4}(t)$, Bid-vector$_{agg,home}$(t), Bid-vector$^{5}_{agg}$(t), Alloc$_{agg}$, Alloc$_{indiv}$
Per aggregator: SummedBid-vector(t), $p^{6}_{equilibrium}$
The temperature information is only applicable for comfort related device nodes.

2.3 Evaluation per use case

2.3.1 Cost-effective use of energy.

The Prosumer[7] operates a household with electricity generators (MicroCHP, PV cells) and consumers. The Prosumer tries to use these devices as cost effectively as possible. 'Cost effective' in this context means maximising economic benefit. The primary goal is not to match production and consumption inside the home (i.e. minimise import to or export from the grid), although this could be a result of the tariff setting currently used. The PowerMatcher technology is used to aggregate bids from individual devices 'behind the meter' and then issue a combined bid to a higher aggregation level. A combined allocation, received at the prosumers level has to be translated to the allocations of the individual devices. A limited number of appliances in one 'virtual' house take part in this setting with some laboratory suppliers and demanders of electricity to guarantee sufficient margin in the equilibrium between supply and demand over a prolonged period.

Characteristic	Summer	Winter	Spring	Autumn
Cloud Coverage<30%	8/8			
T-outside<T-average		8/8		8/8
T-outside>T-average		8/8		

Table 2-1 Number of days to analyse cost optimisation behind the meter with and without coordination

The figures in table above denote the number of days with and without coordination. The day types (working days, non-working days) will be evenly spread, because domestic electricity usage patterns are strongly dependant on the type of day.

2.3.2 Reduce local peak load

In this use case, applying active demand response and generation management of shift-able resources combined with operation of a Distribution agent in a PowerMatcher context for the residential sub-cluster will lead to lowering peaks in the

[1] P denotes the Power; either electrical or thermal
[2] E denotes the electrical Energy; Q the thermal energy
[3] T denotes the temperature
[4] SOC denotes the state-of-charge of a thermal or electrical buffer
[5] A bid vector is an array of increasing/decreasing price/power pairs, giving the information at what price how much power is available.
[6] p denotes the price
[7] 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

distribution system. An important tool for quantifying the result can be found in analyzing load duration curves for certain periods **with** and **without** coordination. Load/generation-duration curves are an important design tool to right-size components in the grid. The effects of conflicting scenarios, like all heat-pumps operating simultaneously and all the PV-equipped houses generating in summer and all micro-CHP equipped houses generating in winter, will be determined and the way the dual-optimization algorithm for energy/capacity resolves the conflict using the PowerMatcher algorithm. The load and generation in kWh are monitored for every device-node in the configuration; so the sum of these as a function of time is all that is needed to determine the graph. In order to verify the data, if possible, measurements of import/export of electricity as function of time will also be done at a transformer station. As the conditions for domestic heating depend on the season and PV yield depends on solar incidence, the data will be analysed in the following reference situations:

Characteristic	Summer	Winter	Spring	Autumn
Cloud Coverage<30%	10/10		10/10	10/10
T-outside<T-average		20/20		
T-outside>T-average			10/10	10/10

Table 2-2 Number of days to analyse for congestion management

Peak loads in grids heavily depend on meteorological circumstances. These pertain to weather predictions and realisations. Therefore, the effect of these on the behaviour of the cluster will also be analysed.

2.3.3 Commercial imbalance reduction

Characteristic	Summer	Winter	Spring	Autumn
Day-ahead profile peaking at 12:00 hrs	20/20			
Day-ahead peaking at 17:00 hrs. / Program with low wind production expected but high realisation		10/10	10/10	10/10
Day-ahead peaking at 17:00 hrs. / Program with high wind production expected but low realisation		10/10	10/10	10/10
Day-ahead peaking at 17:00 hrs. / With expected wind production expected and realisation		10/10	10/10	10/10
Ramp-up peak of imbalance market peak (8:30) on weekdays	20/20	20/20	20/20	20/20

Table 2-3 Number of days to analyse for market interaction

This use case involves all sub-clusters combined in a portfolio operating in a market context. The market context, in this case, consists of complying with a predefined time-depend portfolio program of net demand and supply issued on the basis of planning of the connected resources. PV and wind are planned according to forecasts in a similar way as in the CRISP field test (see Crisp D3.1). An artificial two-layered market mechanism will be represented by using separate business agents, namely. a time-ahead and a balancing agent. No real-time connection to markets is envisioned; some representative historical price patterns will be used, corresponding to typical patterns in certain periods of the year. Firstly, the imbalance in the portfolio will be determined as function of time-of-day. The flexibility of the total cluster will be determined in the form of the total amount of control and reserve power that can be liberated as a function of time and of time-of-year. Furthermore, the achievable ramp-up/ramp-down speed of the Commercial Virtual Power Plant will be determined. The data will be analysed in the reference situations of Table 2-3.
The sample price profiles (hourly APX and quarterly imbalance data will be selected from historic data of the Netherlands in recent years.

2.3.4 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. Nodes involved in this use case are mainly electricity storage units and PV. A similar operational period to show the usage of wind will be selected, in which the alignment of wind peaks with charging of electric storage units e.g. in electrical vehicles will be shown.

Characteristic	Summer	Winter	Spring	Autumn
Cloud Coverage<30%; pre-empt mid-day peak	20/20		10/10	10/10
Wind overproduction overnight and electric vehicle demand		10/10		10/10

Table 2-4 Number of days to analyse valorisation of PV and wind

Forecasts and realisation of solar and wind have to be available in this type of analysis.

2.3.5 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).

Characteristic	Summer	Winter	Spring	Autumn
Evenly spread over the season	20/20	20/20	20/20	20/20

Table 2-5 Number of days to analyse feedback of monitoring

Some user events have to be collected to make the analysis possible.

2.4 Evaluation of the electrical operation

The predefined measurements already have quite a large number of electrical parameters in the form of kW and kWh. If the distribution of participants in the field test allows, a transformer station will also be monitored for Voltage, Current and Power Quality. Part of metering at the node level will be combined with consistency checking of other node's power measurements.

2.5 Economic Evaluation

Apart from use case objective and electrical operation evaluation, there will also be an economic evaluation based on future business models. The context will be defined by a market price setting as defined earlier and also by a number of alternative real-time end-user tariff schemes, reflecting the increased role of the consumer in delivering value to the system (e.g. ancillary services, imbalance reduction services etc). These economic evaluations are closely connected to the use case business logics and the electrical operation. Therefore, they will not be further discussed here.

2.6 ICT infrastructure evaluation

The ICT infrastructure, built in field-test A, is extensive. The same holds for the heterogeneity of the software and hardware configuration. The design of the system was done minimizing risk by using COTS-components in the architecture. Apart from the software serving the use cases, configuration and version management were also included as use cases. Looking to the dynamics of the primary user process, which defines the necessary intensity of message exchange and storage frequency of data, the concept implementation of the network over ADSL/POTS is sufficient to cope with the required storage of data of primary process parameters for analysis.

2.6.1 Scope, analysis and requirement compliance validation

From a technical point of view, in the evaluation, the overall performance of the system will be considered. From the communication point of view, this pertains to the application's response times, connection set-up times, delays in protocol message exchange and databases read and write operations during real-time operation of the total cluster. From the application point of view, the logging mechanism and use to serve the scientific application will be considered. The used infrastructure was derived from the technical requirements; user requirements are also important as a large amount of the appliances, taking part in the field-test, are in end-user premises.

During set-up of the field-test, procedures will be defined to streamline the build-up and deployment process. Furthermore, during testing there will be user portal to inspect operations and give feedback. Data from these user interactions will be analyzed after the test.
Computer codes will not be instrumented to determine figures to analyse; if certain bottlenecks appear to exist, steps will be taken during the development path. The approach will be merely driven by analyzing events and logs during building, deployment, and operation of the system.
The limit on acceptable figures is determined by the requirement specification and the dynamics of the primary process served by the agent.

3. Definition of test and evaluation of Demo B

3.1 Introduction

Mas Roig is an isolated power network. The connection to the general power network is going to be simulated using one of the inverters in master mode (Grid Forming). The system that will be developed will include two main parts, 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 the communication process.

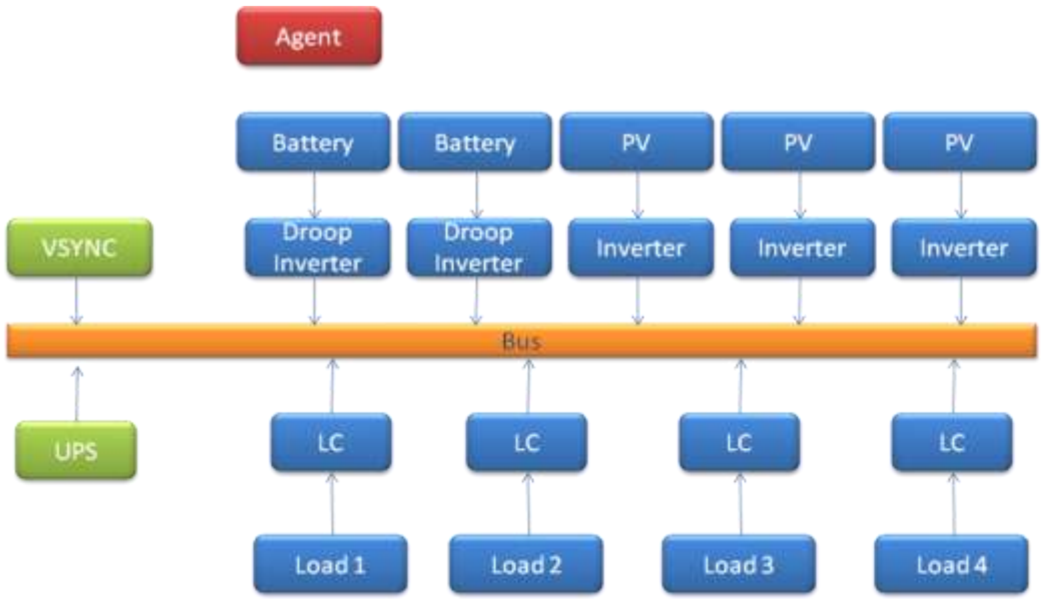

Figure 3-1. Demo B site schematic installation

The Demo B objective is to show how small grids with a high share of DER and RES, connected to the main grid, can be kept stable and contribute to voltage and frequency fluctuation by using the **INTEGRAL** Integrated ICT-platform based Distributed Control (IIDC) system. Furthermore, the operation of the system in islanding mode as well black start or short circuit will be investigated. Products developed based on this technology will allow the control (for instance to disconnect such micro-grids and the internal loads if needed) to keep the stability of the overall grid, without any consequences for its users, and therefore, it will be able to keep the system stability by itself. Figure 3-1 presents the general structure of the system in Mas Roig which also includes the collaboration with another research project called VSYNC. . In the VSYNC project a bi-directional inverter is developed in order to provide ancillary services to the grid. This inverter can be used and tested in the Demo B.

The scope of the Demo B experiment is to test the operation of the distributed architecture under emergency situations, such as voltage and frequency variations. Next, the definition of the various scenarios will be presented.

3.1.1 Voltage/Frequency variations

In this scenario, the inverters support the frequency/voltage and the loads are supporting the inverter as stated in the D6.1-2. The verification procedure will include:

- How the system affected the frequency/voltage. More specifically, which percentage of the variation was confronted by the system. It should be noted that since the system is isolated the variation may be larger than acceptable in the main grid.
- The amount of energy provided by the system (inverters) in order to support the fluctuations.
- The amount of energy the loads have shed in order to support the inverters.

Although the Demo B includes a technical experiment, it is very important to verify the amount of energy spent for the voltage/frequency support as well the capacity/SOC (state of charge) of the inverters that are committed to this operation.

3.1.2 Intentional islanding/Black Start

In this case, the main parameter is the time the system stays in islanding mode as well the time it takes to start up. However, it is not the only parameter since as stated before, the system is prepared before the black out in order to cope with the event. The batteries should be full and this means that the amount of energy stored there will not be used elsewhere.

So one parameter that should be measured is:

- The amount of energy provided by the system to the inverters in order to support the SOC.
- The amount of energy the loads have shed in order to support the inverters.

After the event the following parameters are measured:

- The amount of energy provided by the inverters.
- The amount of energy the loads have shed in order to support the inverters.
- The time the system is kept in island mode.

It is obvious that multiple experiments will take place in order to acquire a precise knowledge of the system behaviour.

3.1.3 Operation after a short circuit.

In this experiment the performance of the protection devises within the Demo B will be evaluated. More specifically, the behaviour of the inverters during the fault as well their protection equipment will be tested.

3.1.4 Structure of the tests

The evaluation procedure has two main parts. The first part evaluates the system operation and the ICT solution in terms of efficiency, applicability and cost. The second part is related to the electrical operation and evaluates the efficiency of the electrical operation of the system.

3.2 Evaluation of the system operation

The system evaluation has three main parts:

1. Evaluation of the Development process
2. Evaluation of the Control Algorithm
3. Evaluation of ICT infrastructure

This analysis of the various parts is provided next.

3.2.1 Development Process

Part of the evaluation process is the monitoring of the system installation/development. The evaluation of the development process is a useful tool for next implementations as it will clearly describe the critical parts of a system. For the test site the following should be taken into account:

- The difficulties occurred during the development/installation of the system
- The solutions that were adopted in order to deal with the difficulties
- The affect of solutions upon the system operation.

More specific the following should be monitored / evaluated:

ID	Event	Description
1	Installation of Electrical Equipment	Problems during the installation and necessary modifications in the system structure of Mas Roig
2	Control Equipment installation	Problems during the installation and necessary modifications in the system structure of Mas Roig
3	Communication System	Problems during the installation and necessary modifications in the system structure of Mas Roig
4	Current Electrical Appliances	Problems to the electrical appliances because of the new equipment

Table 3-1 List of Events.

For the list of the most serious problems it should be stated the affect on the control algorithm or the system operation.

3.2.2 General Control Concept/Algorithm:

Regarding the General Control Concept the ICT infrastructure should be evaluated. The JADE platform is a quite complicated set of libraries. Furthermore, the operation of the algorithm is highly depended on complex conversations between the agents, thus several issues may affect the algorithm. More specifically, the following questions should be evaluated:

ID	ICT	Description
1	Processor Capability	Is the processor power sufficient for the control system (execution time)
2	Communication System	Problems due to communication delays.
3	Software Package	The selected software package create problems/difficulties/extra processor power (execution time/ amount of data exchange for non monitoring purposes)

Table 3-2 Evaluation of the Control Concept.

The overall scope of this part is to describe the possible adaptation to the control algorithm in order to operate.

3.2.3 ICT Performance

The last part focuses on the ICT performance of key aspect for the demo in Mas Roig. The previous tests focus on the performance of the system in the Demo site. However, this test tries to evaluate the system performance in terms of mass application.

More specifically, for Demo B the following success factors should be evaluated:

3.2.3.1 Scalability

In order to evaluate the system scalability the following evaluation procedure can be selected:

1. System operation with ½ of the ZigBee nodes
2. System operation with 1/3 of the ZigBee nodes
3. System operation with all of the ZigBee nodes
4. System operation with simplified control algorithms

3.2.3.2 Open access

Open Access is the capability to cooperate with other components/hardware etc. The following procedures should be evaluated:

1. Plug n' play procedures.
2. Procedure to add an inverter from different vendor.
3. Procedure for communication with inverters/load controllers

3.2.3.3 Affordability

1. Enumeration of "off-the-shelf" components/software packages
2. Cost estimation in mass production (for non commercial components)

3.2.3.4 Reliability

The reliability tests will evaluate the stability of the various components. In a real environment procedures, like the "watchdog", are significant in order to increase reliability. Therefore, the main test is to investigate the system performance under software, hardware and communication failures.

3.2.3.5 Security

ICT security is one critical part of the development of any software program especially when it is based on communication via Internet. The main focus of the evaluation is to check whether or the components are compatible and operate correctly under normal network restrictions.

3.3 Evaluation of the Electrical Operation

The goal of the evaluation of the electrical operation is to check whether the new algorithm is able to reach the desired performance. The analysis of the test as well the quality factors and the list of measurements for the various tests is described below.

3.3.1 Voltage/Frequency Variations

The quality factors are:

ID	Description	refresh
1	Duration of the event	sec
2	Amount of Energy Consumed	kWh
3	Max/Min Voltage Level	1 sec
4	Max/Min Frequency	1 min

Table 3-3 General Values for Voltage/Frequency Variations

The evaluation process has two main parts:

1. System Monitoring Without Disturbances
2. System Monitoring With Disturbances.

The evaluation process will be held in cycles each lasts two weeks. The first week is the system monitoring process where no intentional disturbances occur. This phase is necessary in order to understand the system operation/ performance. During the second week, the incidents are taken place randomly in various hours of the day.

3.3.1.1 Measuring

The list of measurements are:

ID	Name	Description	refresh
1	System Frequency	The Frequency in Mas Roig	1 sec
2	Total Production	Total Production of PV/Wind and diesel Generator	1 sec
3	Total Consumption	Total Consumption of the Loads	1 sec
4	Total Energy Production		1 min
5	Total Energy Consumption		1 min

Table 3-4 List of measurements

In the above table, the difference between total production and total consumption is due to the losses especially in the battery charging. Empirically, the efficiency of the battery is approximately 70%.

ID	Name	Description	refresh
1	Production P	Active Power of the Battery inverter	1 sec
2	Production Q	Reactive Power of the Battery inverter	1 sec
3	Consumption P	Active Power Consumption of the Battery inverter	1 sec
4	Consumption Q	Reactive Power Consumption of the Battery inverter	1 sec
5	Batteries Voltage	Battery Voltage	1 min
6	Output Voltage	Voltage in the Output of the inverter	1 sec
7	SOC	State of Charge	1 min

Table 3-5 Battery Inverter

ID	Name	Description	refresh
1	Production P	Active Power of the Battery inverter	1 sec
2	Consumption P	Active Power Consumption of the Battery inverter	1 sec
3	Consumption Q	Reactive Power Consumption of the Battery inverter	1 sec
4	Output Voltage	Voltage in the Output of the inverter	1 sec

Table 3-6 PV/Wind Inverter

ID	Name	Description	refresh
1	Consumption P	Active Power Consumption	1 sec
2	Consumption Q	Reactive Power Consumption	1 sec
3	Output Voltage	Voltage in the Output of the inverter	1 sec

Table 3-7 Load Nodes

3.3.2 Intentional Islanding/Black Start

The quality factors are:

ID	Description	refresh
1	Duration of the event	sec
2	Amount of Energy Consumed	kWh
3	Energy Stored Before the Event	
4	Time to Start Up.	1 min

Table 3-8 General Values for Intentional Islanding/Black Start

The evaluation process should take into account that the system state is critical for this case. Therefore, we should not monitor the system after the event but also at least one day beforehand. Furthermore, several other cases should be taken into account:

ID	Previous Day	After the Event
1	No Wind/Sun and High Load	No Wind/Sun and High Load
2	Medium Wind/Sun and High Load	No Wind/Sun and High Load
3	Medium Wind/Sun and Low Load	No Wind/Sun and High Load
4	No Wind/Sun and High Load	No Wind/Sun and High Load
5	Other combination	

Table 3-9 Cases for Intentional Islanding/Black Start

3.3.2.1 Measuring

The list of measurements are:

ID	Name	Description	refresh
1	System Frequency	The Frequency in Mas Roig	1 sec
2	Total Production	Total Production of PV/Wind and diesel Generator	1 sec
3	Total Consumption	Total Consumption in the Loads	1 sec
4	Total Energy Production		1 min
5	Total Energy Consumption		1 min

Table 3-10 List of measurements

ID	Name	Description	refresh
1	Production P	Active Power of the Battery inverter	1 sec
2	Production Q	Reactive Power of the Battery inverter	1 sec
3	Consumption P	Active Power Consumption of the Battery inverter	1 sec
4	Consumption Q	Reactive Power Consumption of the Battery inverter	1 sec
5	Batteries Voltage	Battery Voltage	1 min
6	Output Voltage	Voltage in the Output of the inverter	1 sec
7	SOC	State of Charge	1 min

Table 3-11 Battery Inverter

ID	Name	Description	refresh
1	Production P	Active Power of the Battery inverter	1 sec
2	Consumption P	Active Power Consumption of the Battery inverter	1 sec
3	Consumption Q	Reactive Power Consumption of the Battery inverter	1 sec
4	Output Voltage	Voltage in the Output of the inverter	1 sec

Table 3-12 PV/Wind Inverter

ID	Name	Description	refresh

1	Consumption P	Active Power Consumption	1 sec
2	Consumption Q	Reactive Power Consumption	1 sec
3	Output Voltage	Voltage in the Output of the inverter	1 sec

Table 3-13 Load Nodes

4. Definition of test and evaluation of Demo C

4.1 Introduction

The demonstration C aims to create self-healing abilities for distribution networks after important disturbances (such as short-circuit). The challenge on the fast location of faulty section(s), then eliminate them and automatically reenergize the sane parts of the network.

This demonstration, which deals with emergency operation, will take place at Grenoble Electrical Engineering Laboratory (G2Elab) at the Grenoble Institute of Technology (PREDIS platform). The test bench being developed aims to prove the feasibility of the self-healing concept of distribution network with help of **INTEGRAL** Integrated ICT-platform based Distributed Control (IIDC) system.

A μanalogical network zooms out some real EDF's distribution feeders (20 kV). It is widely described in the D7.1 and D7.2, the topology of demo network is given again in Figure 4-1. The entire system can be divided into two main parts:

- Electrical part including every electrical elements and devices such as line, transformer, generator, load, protection devices, for instance.
- ICT part including advanced Remote Terminal Units (RTUs) or Intelligent Electronic Devices (IEDs) such as Remote Fault Indicator (FI), Fault Recorder (FR), Intelligent agent system and also the communication system between each and another.

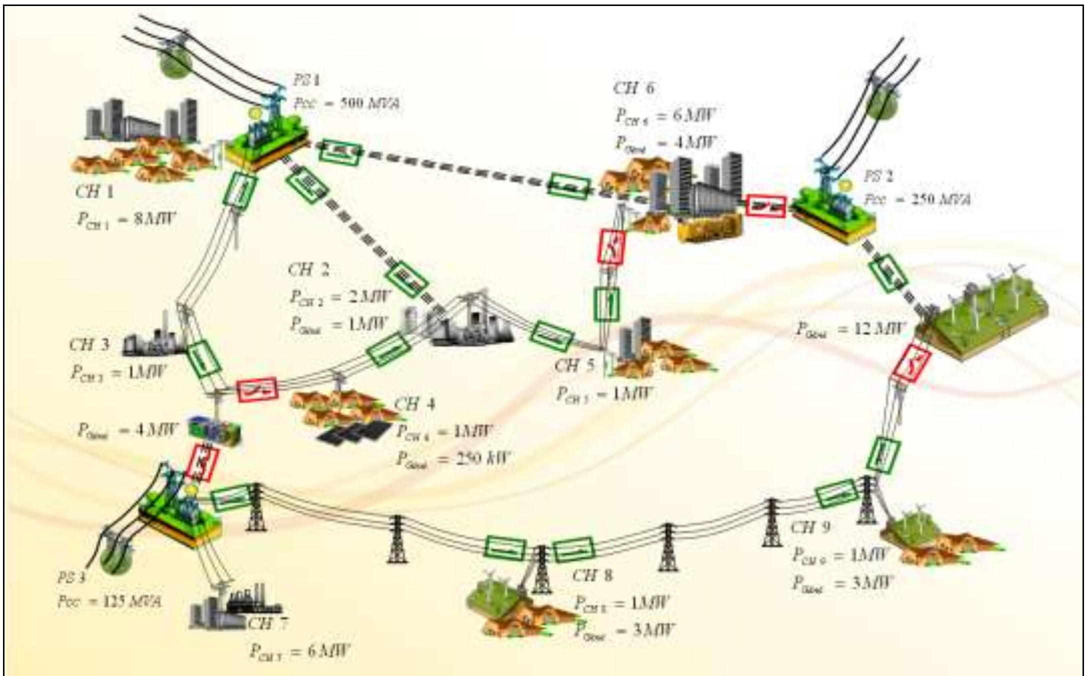

Figure 4-1. Electrical infrastructure of Demonstration C

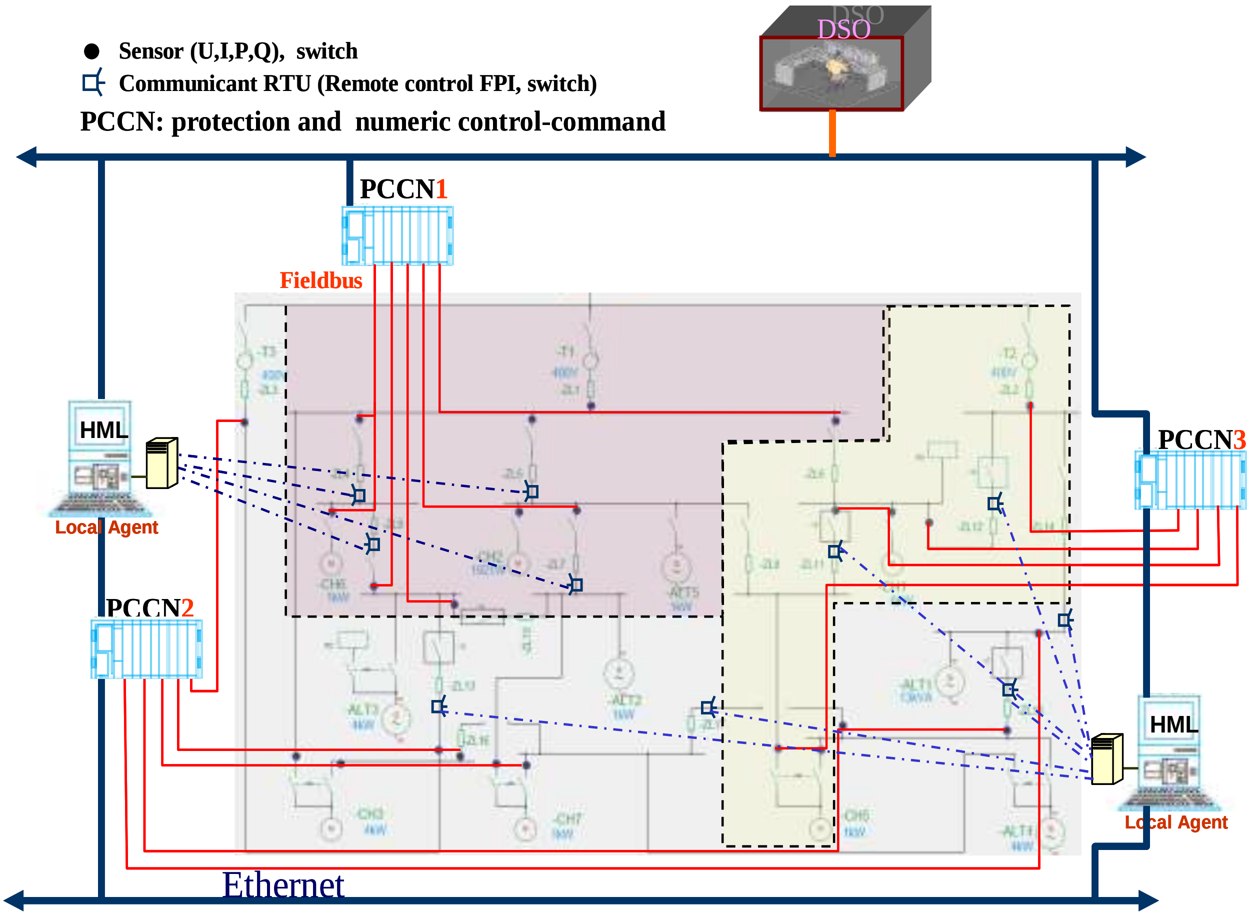

Figure 4-2. IIDC infrastructure for Demonstration C

The self-healing functionalities are integrated into local intelligent agents developed under the MATLAB environment. The OPC technology should be used in order to have a standardized set for data exchange between every software application. MATLAB - OPC Toolbox which could play a role of an OPC Client, could retrieve the necessary information from OPC server associated with the hardware (IED, RTU,etc) or with the SCADA centre (DSO on Figure 4-2). Afterward, advanced control and batch execution will be carried out to achieve the final result of self-healing functionalities.
After a fault, classical protection scheme is operating the breaker of the feeders. Then, a local agent (associated to this part of the network) is locating the faulty part, and chooses the correct switches to operate. This set of switches is then sent to DSO or substation automation (PCCNx) for manual or automatic operations.

4.2 Evaluation of the system operation

4.2.1 Development Process

Demonstration C aims to develop a test bench which handle emergency operation of distribution system in presence of large amount of DER/RER. The objective of this test bench is to evaluate the crucial role of Information and communication technologies (ICT) system and advanced distributed automation devices (ADA) in self-healing application in distribution network after occurrence of an important disturbance. The development process of the demonstration need to be evaluated, in order to ensure the efficiency of the self-healing functionalities and cost-effective of test bench. The mains steps in development process include the following:

- Communication requirement for the entire demonstration system
- Intelligent ICT switches (coordination with BTH)
- Building the “home made” RTUs with TCP/IP communication abilities
- Interconnecting industrial or home made RTUs with agents through OPC servers or others Inter-Process Communications (IPC)
- Link between OPC servers and MATLAB with the OPC toobox
- Link between MATLAB Toolbox & self-healing functionalities
- Self healing functions testing with real time simulator
- Closed loop between MATLAB and SCADA system

Although the demonstration C is specified for emergency operation of distribution network, there are also some difficulties/challenges associated with the function of ICT and SCADA system. To deal with these difficulties, along with an important working force which is building solutions, industrial tools (OPC standards and PCVue to build a SCADA software) and state of the art scientific tool (MATLAB, MATLAB Simulink and OPC toolbox for MATLAB) were adopted. Furthermore, the tight cooperation with the ICT experts from Blekinge University of Technology (Partner in INTEGRAL Consortium) is planed to resolve the problem concerning intelligent ICT switches. These solutions give a wide flexibility which will be able to allow the INTEGRAL consortium to give guidelines for the IIDC sizing (as computerization and communication strengths).

4.2.2 General Control Concept/Algorithm:

A fault detection and location algorithm for distribution networks was developed in GIE-IDEA in cooperation with G2Elab (Grenoble InP), using in combination FIs results with fault distance computation. The advantages of this method consist in its high autonomous level for fault location with an associated ICT infrastructure. This method is very efficient in case that there are many branches and ramifications in distribution network.
The detailed description of these algorithms has been mentioned in deliverable D2.2, the function block scheme is presented again in figure **Fout! Verwijzingsbron niet gevonden.**

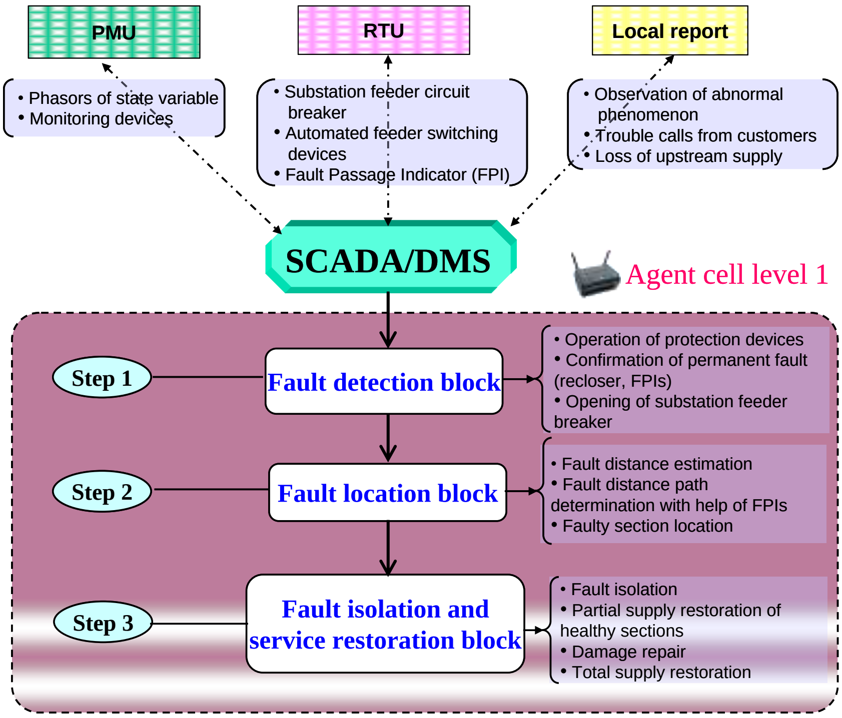

Figure 4-3 .Self-healing function for agent cell level 1

This distribution network works normally in opened loop operation. Firstly, when a fault appears in the network, the re-closing sequences are carried out to determine the permanent fault existence. If the re-closing procedure is not successful, the main circuit breaker is opened and an alarm is sent to the operator to inform him about the existing feeder no more supplied. After the acquisition of information about the emergency state from the RTUs, the fault distance evaluation will be computed at local intelligent agent. The estimation value will be sent to the system operator (DSO). The operator can know the distance of fault from the substation. Then, the signalling provided by FIs (both non-directional and directional) allows operator to determine the correct fault path among many paths corresponding the estimated distance. Finally, the system operator can fix the exact faulty section in analyzing the information resulted from FIs, using eventually some intelligent algorithm of selection. After the fault is located, the operators have to execute several operations to reenergize the sane portions of network and reduce as maximal as possible the customers affected by the fault.

The specified ICT Infrastructure being built for the demonstration C in order to effectively achieve the self-healing objectives such as reduction of outage time and outage cost. Until now, no adaptation is needed, as far as the infrastructure is completely dedicated for the demonstration.

4.2.3 ICT Performance

The performance of ICT system for Demo C is evaluated through following success factors:

- *Communication performance*

The self healing functions deal with the fast reconfiguration of remotely controllable switches to quickly isolate the sane part of the network after the action of the protective scheme (protective relays with breaker at the substation, feeder by feeder, or distributed protective relays associated with breakers). This self-healing process is then not linked with protective relay coordination and does not need real time communication performance related protection systems (down to few ms for usual differential protections). Nevertheless, if a near real time communication performance is achieved for the agent, the customers will be re-energized quickly. The goal of our agent is to reach a service restoration faster than the actual service restoration with a human (operator) in the loop. This means that the overall performance (sensor + communication + agent computerization + communication to switches + execution + feeder breaker action) is around 30 seconds (compare to an average of 240 seconds today).
The demo C will try to evaluate the performance (time lag) of its ICT system (from sensor to agent through OPC server or other) and try to give guidelines for industrial system.

- *Scalability*

Because the ICT system for demonstration C is designed for self-healing functionalities of distribution network in emergency operation, the implementation of information technology hardware and software is the most cost-effective solution. However, others high level functionalities for DMS may be integrated into the extant ICT framework. For the functionalities, which can use the same data from the measurement system, the existing RTUs, IEDs may be reused more economically. But, with the new function and data so diverse, the estimated cost for modifying the existing system need to be taken into account.

- *Open access*

The ICT solution for the demonstration C using the most common industrial standard of information and communication such as (OPC or equivalent), TCP/IP standard and so on) helps for the plug and play ability and the low cost of the solution.

- *Reliability*

The solution of a DSO that manage and take the information from the local agent to make decision can enhance the reliability of the whole system. However, to flexibly archive the restoration service, the local agents must be intelligently coordinated.

- Security

Communication networks used in Demo C are a private copper local area network. They function separately and are not routed to the Internet. However, this kind of communication mainly has to face internal threats to its network. A password function is built into all networking software, but its function is mainly to "*keep the bad boys out*"

- *Maintainability*

It depends on the guidelines of INTEGRAL for industrial standardization.

4.3 Evaluation of the electrical operation

According to the objective, the following five scenarios will take place in Demo C.

4.3.1 Fast fault detection and isolation (location robustness)

- Description

On the demonstration network, different fault locations will be tested. DSO will use the high level functionality associating with the ADA devices (Fault Passage Indicator, remote control switches…) in order to quickly detect and isolation the faulty section.
Expected result of these scenarios is to evaluate whether the fault detection and location mechanism is robust for every fault location?

- List of variables should be monitored

Electrical variables	ICT signals
I_{fault} from substation (RMS value) I_{fault} from DGs (RMS value) U_{fault} (RMS value)	• Fault Indicator alarm signals (both directional or non- directional). • Remote control switches status.

- Success factor

Faulty section is located and isolated for wherever fault location

4.3.2 Fast fault detection and isolation (fault type)

- Description

On the demonstration network, different short circuits will be tested (three phases, two phases, single phase with or without grounding). DSO will use the high level functionality associating with the ADA devices (Fault Passage Indicator, remote control switches…) in order to quickly detect and isolation the faulty section.
Expected result of these scenarios is to evaluate whether the fault detection and location mechanism is robust for different fault types.

- List of variables should be monitored

Electrical variables	IEDs signals
$I_{fault\text{ - direct, inverse and zero sequence}}$ from substation (RMS value) $I_{fault\text{ - direct, inverse and zero sequence}}$ (RMS value) from DGs (RMS value) $U_{fault\text{ - direct, inverse and zero sequence}}$ (RMS value)	• Fault Indicator alarm signals (both directional or non- directional). • Remote control switches status.

- Success factor

Faulty section is located and isolated for whatever fault types

4.3.3 Fast service restoration processes and communication performances.

- Description

On the demonstration network, short circuit and self healing function will be tested. DSO will then use the high level functionality associating with the ADA devices (Fault Passage Indicator, remote control switches…) in order to quickly detect and isolation the faulty section. The performances of the communication means will be sized. Several bandwidth and latency will be applied between the RTUSs and the agents.
Expected result of these scenarios is to evaluate the communication performance during service restoration process and its impact on outage time and cost.

- List of variables should be monitored

Electrical variables	IEDs signals
I_{fault} from substation (RMS value) I_{fault} from DGs (RMS value) U_{fault} (RMS value)	• Fault Indicator alarm signals (both directional or non- directional). • Remote control switches status. • Timestamps and quality of signal communication.

- Success factor

The time needed to reenergize the sane portion of network.

4.3.4 Fast fault detection and isolation in respect with the grounding of the substation

- Description

On the demonstration network, short circuits (different nature) and self healing function will be tested in function of grounding type. DSO will then use the high level functionality associating with the ADA devices (Fault Passage Indicator, remote control switches…) in order to quickly detect and isolation the faulty section even in various grounding condition.

Expected result of these scenarios is to evaluate the impact of grounding mode at substation on the earth fault detection and location mechanism.

- List of variables should be monitored

Electrical variables	IEDs signals
$I_{fault\text{ - direct, inverse and zero sequence}}$ from substation (RMS value) $I_{fault\text{ - direct, inverse and zero sequence}}$ (RMS value) from DGs (RMS value) $U_{fault\text{ - direct, inverse and zero sequence}}$ (RMS value) $I_{fault}(t)$ @5kHz for Petersen Coil	• Fault Indicator alarm signals (both directional or non- directional). • Remote control switches status.

- Success factor

Faulty section is located and isolated for whatever grounding mode.

4.3.5 Fast fault detection and isolation depending on the power flow inside the Distribution Network

- Description

On the demonstration network, different short circuits will be tested with various loading and sourcing conditions. DSO will use the high level functionality associating with the ADA devices (Fault Passage Indicator, remote control switches…) in order to quickly detect and isolation the faulty section.
Expected result of these scenarios is to evaluate the impact of power flow inside distribution network on fault detection and location mechanism.

- List of variables should be monitored

Electrical variables	IEDs signals
I_{load} (RMS value) I_{fault} from substation (RMS value) I_{fault} from DGs (RMS value) U_{fault} (RMS value)	• Fault Indicator alarm signals (both directional or non- directional). • Remote control switches status.

- Success factor

Faulty section is determined for whatever power flow level.

4.4 Overall Evaluation

The principal data needed for fault distance computation using in Demonstration C is the fault current and voltage measured values. Hence, the efficiency of the fault

distance computation depends strongly on performance of measurement equipments.
In the case, where the fault occurs close to the substation, the large fault current may cause the saturation of measurement transformer and deteriorate the accuracy of measured values.
Other problem which may affect the accuracy of fault distance computation is the load current superposed on the measured fault current. Some assumptions have been proposed during the development of algorithms. Moreover, although the load current model change significantly depends on the load variation in the network, the load behaviour on network could be overseen as much as possible thanks to the intelligent RTUs system. On the other hand, the measured fault current at DGs and at substation need to be synchronized to enhance the fault distance computation efficiency.

For the fault location, the performance of algorithms relies on the abilities of Fault Indicators. The "home-made" Fault Indicator construction could not assure that the direction function will be able to be correctly integrated. Unfortunately, this function would be very important in case of small fault current like unearthed or compensated fault.

Service restoration qualities need a perfect knowledge about network topologies and the real time situation of network after the fault occurrence (database of the DSO operator). With the IIDC framework developing for the Demonstration, the network topology could be analysed and technical constraints are checked in real time.
Additionally, the outage duration and cost depends on the number of remotely controlled switches installed in network. With the assumption that the 100% of switches for the demo C have the remote control ability, both the system operator and the customer could be benefit from the minimum outage cost.

5. Definition of test and evaluation of Integral System

5.1 Introduction

Scope of this part is to provide an overall system evaluation according to formal methodology. As stated in the description of work the three demo sites should be considered as an integral system the three control algorithms can be incorporated into one single system. Therefore, the scope of this chapter is to present a general methodology that will allow the overall evaluation of the system. The methodology is based on the standard ISO 9126 and on its extended ISO model discussed below.

5.2 ISO 9126

ISO 9126 is an international standard for the evaluation of software quality. A structured way to evaluate software architecture (and it may well apply to system architecture) can be done using the Extended ISO 9126 model. The Extended ISO 9126 model describes software quality in terms of quality characteristics and sub-characteristics. The fundamental objective of this standard is to address some of the well known human biases that can adversely effects the delivery and perception of a software development project.

The quality model established in the first part of the standard, ISO 9126-1, classifies software quality in a structured set of characteristics and sub-characteristics. The characteristics defined are:

• **Functionality**: a set of attributes that bear on the existence of a set of functions and their specified properties. The functions are those that satisfy stated or implied needs.
• **Reliability**: a set of attributes that bear on the capability of software to maintain its level of performance under stated conditions for a stated period of time
• **Usability**: a set of attributes that bear on the effort needed for use, and on the individual assessment of such use, by a stated or implied set of users.
• **Efficiency**: a set of attributes that bear on the relationship between the level of performance of the software and the amount of resources used, under stated conditions.
• **Maintainability**: a set of attributes that bear on the effort needed to make specified modifications.
• **Portability**: a set of attributes that bear on the ability of software to be transferred from one environment to another.

For each sub-characteristic, a number of indicators are defined for this quality sub-characteristic. The sub-characteristics are presented in the next figure:

Figure 5-1 The quality model of ISO 9126

For each sub-characteristic a number of indicators are defined for this quality sub-characteristic.
During the evaluation of the Integral demo site the following steps should be considered.

1. Define the quality sub-characteristics for final system
2. Define which of them are implemented in the architecture of each individual field test.
3. Assess the individual field test systems with respect to these sub-characteristics. I.e. define the indicators to be measured for each field test

4. Aggregate those sub-characteristics into quality factors that could be shared between test sites.

The definition of the sub-characteristics as well as their evaluation will be done while the tests are in progress. A quality factor for each main characteristic will be defined and shared between the test sites. The overall quality assessment among the demo sites will be done at the end of the WP8. An integrated formula should be used (such as maximum Hinfinit or H2) to scale the different quality factor which doesn't take into account exactly the same sub-characteristics.