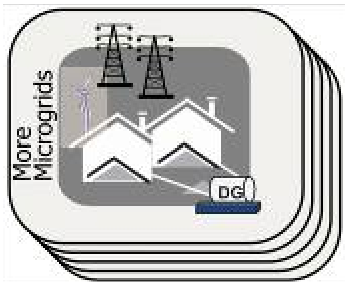

MoreMicroGrids

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WORK PACKAGE F

DF1. Report on field tests for interconnected mode

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Contents

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1. Introduction

The progress of the actual society is strongly supported on the energy utilization. Nowadays, one of the main challenges is the transformation of enough energy from its primary resource to an electrical vector. The more the human development, the biggest the energy is required to sustain it.

Traditionally, the primary resource from which the energy has been obtained, has been based on fossil deposit which has a limited nature. New alternatives to substitute the actual predominant non-renewable resources by a more sustainable approach, at the time that the environment issues are fit, seems to be one of the paradigms of the beginnings of the XXI century.

However, a virtual increment on the energy generated can be attained if the policies about consumption are modified. Concepts like the Demand Side Management, generation within or close to the consumption centres, are tactics undertaken to increase the apparent effect of the energy available, through a more rational use of it.

One important alternative to put up with these troubles is the µGrid concept, wherein the generation and the consumption are considered in the same scale of decision. As happens with whatever new idea which tries to oppose the formers, a program to demonstrate its achievement needs to be developed, in order to assure its feasibility.

In this aspect, controllable generation along with controllable loads needs to be gathered in order to operate them in a µGrid environment and survey the outcomes.

Within the LABEIN DG laboratory facilities, several alternative µGrid configurations could be developed and deployed to test these new issues related with the coming alternatives for energy supply.

The MORE MICROGRIDS project presents several pilot test cases including real customer installations and utility owned feeders as well as laboratories and these test cases serve to deploy hardware and software prototypes for the evaluation of the developed concepts. Each one of these two separate alternatives does present advantages and disadvantages.

Testing new concepts and mainly prototypes on real networks is perfectly possible but implies higher costs and / or undesired risks. Under normal circumstances, when commercial companies aim to release a new product a large set of tests and qualifications for standardization are involved before the product is available for general use. This process requires not only intense work effort but also budget for certification and validation testing. In terms of risk, for instance, other customers connected to the LV grid may get exposed to security problems (higher fault currents, step and touch potentials…) due to bugs and unexpected sequences of events face not to mention a possible reduced quality of supply.

The testing done at LABEIN's test grid is provides as testing environment some other benefits:

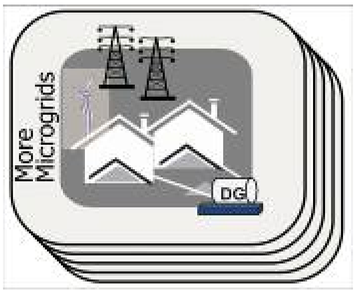
- Most of the equipment were already available, diesel units, µTurbine, flywheel, load banks, etc. so a relatively complex simulation environment could be built with negligible costs.
- AC/AC modules enable the use of the diesel units in both islanded and grid connected mode. The AC/AC control development (produced by Labein at WPA) and testing cause no security risk or damaged equipment (far from a few fuses and small auxiliary devices).
- The static switch closing and opening operations could be completed with large effects in power quality terms but without any adverse consequences on real customers.
- The control system (produced by Labein at WPB) is deployed to an available set of equipment having to integrate communication protocols and physical links. This provides first hand experience of integration issues.
- The implementation of the still draft IEC 61850-7-420 (produced by Labein at WPB / WPE) as unique equipment data model and the need to interface with available equipment outlines gaps, difficulties in mapping real and model concepts, etc.
- The use of load banks allow to simulate thought scaling almost any load profile and environment but avoid affecting real customers with unexpected trippings, voltage excursions, frequency drifts and other power quality events.
- The local software agents may be configured easily so different configuration of sources may be emulated with distinct energy bid strategies. Direct control of units permits introducing unexpected events without acting upon customer owned facilities and assets.

In brief, laboratory facilities present a larger flexibility for testing purposes while minimizes the risks of side effects over third parties and avoids falling into regulated business and its strict normative

The full report is divided in several chapters, the first part is devoted to describe the DG testing environment elements and facilities and the following sections are concentrated in exposing concrete tests or study cases:

- Static switch operation and dynamic behaviour with power quality measurements.
- Energy Management System - Secondary regulation in grid connected and islanded operation modes.

Finally, the last section describes the control and protection system based on IEC 61850 compliant equipment deployed and configured to handle both the grid connected and the isolated operation modes.



MoreMicroGrids

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Part I – Labein's µGrid description

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Contents

1. Introduction

This document describes LABEIN’s Distributed Generation laboratory facilities, main distribution network topology and characteristics and the available equipment. Different alternative µGrid configurations could be implemented to obtain distinct study cases, each one aimed towards one specific objective testing purpose.

2. MV Topology

LABEIN's µGrid is coupled to the 30 kV radial network feeding the 'Parque Tecnológico of Bizkaia' as showed on Figure 2-1. Labein's location at the MV network is denoted by the red circle.

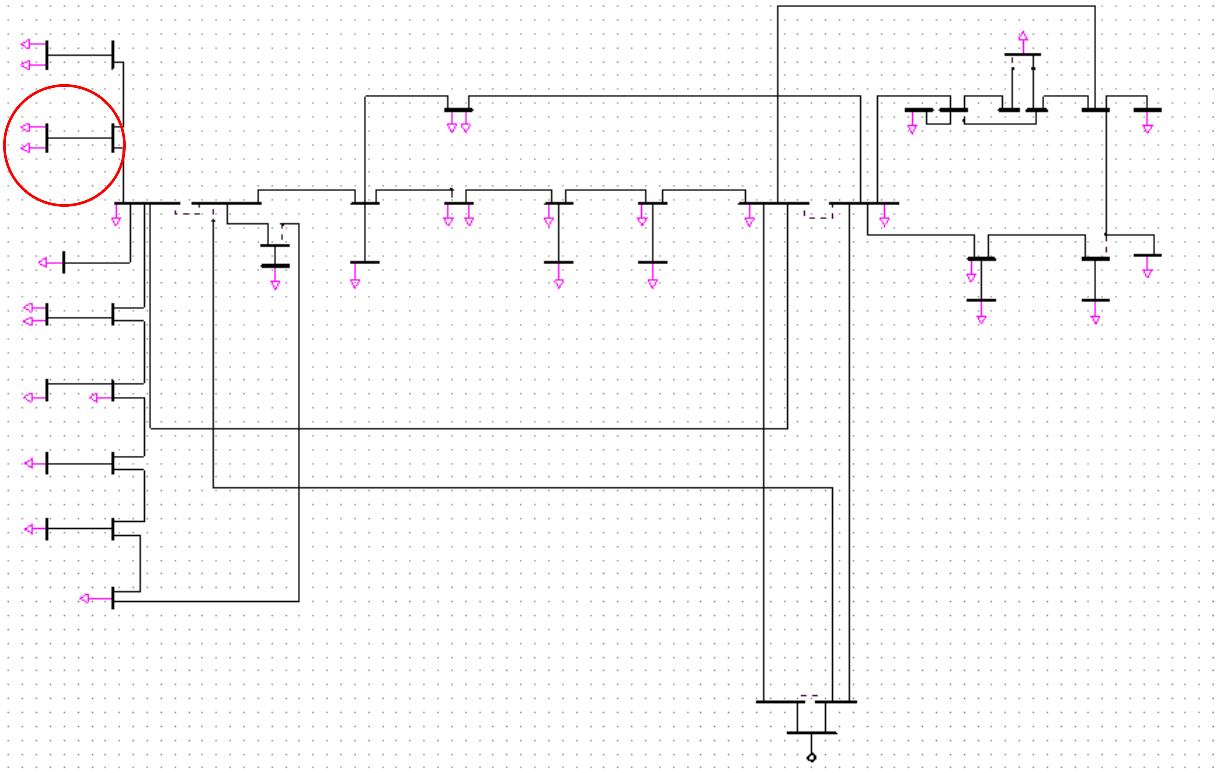

Figure 2-1: MV Topology

It should be noticed that network design (Figure 2-1) is meshed for security reasons but network operation is radial (dashed lines indicate open switching devices).

Two 1250 kVA rated transformers are in charge of adapting the MV voltage to the low voltage levels distinctive of the offices consumption. The integrated control system enables only one transformer until the consumption rises above 90% of the operating unit although both transformers are in parallel on permanent basis. Under normal consumption patterns only one transformer is being used leaving the second unit on open circuit.

The MV network strength is denoted by the short circuit currents:

- Icc (three phase short circuit): 6,608A.

- Icc (single phase short circuit): 3,443A.

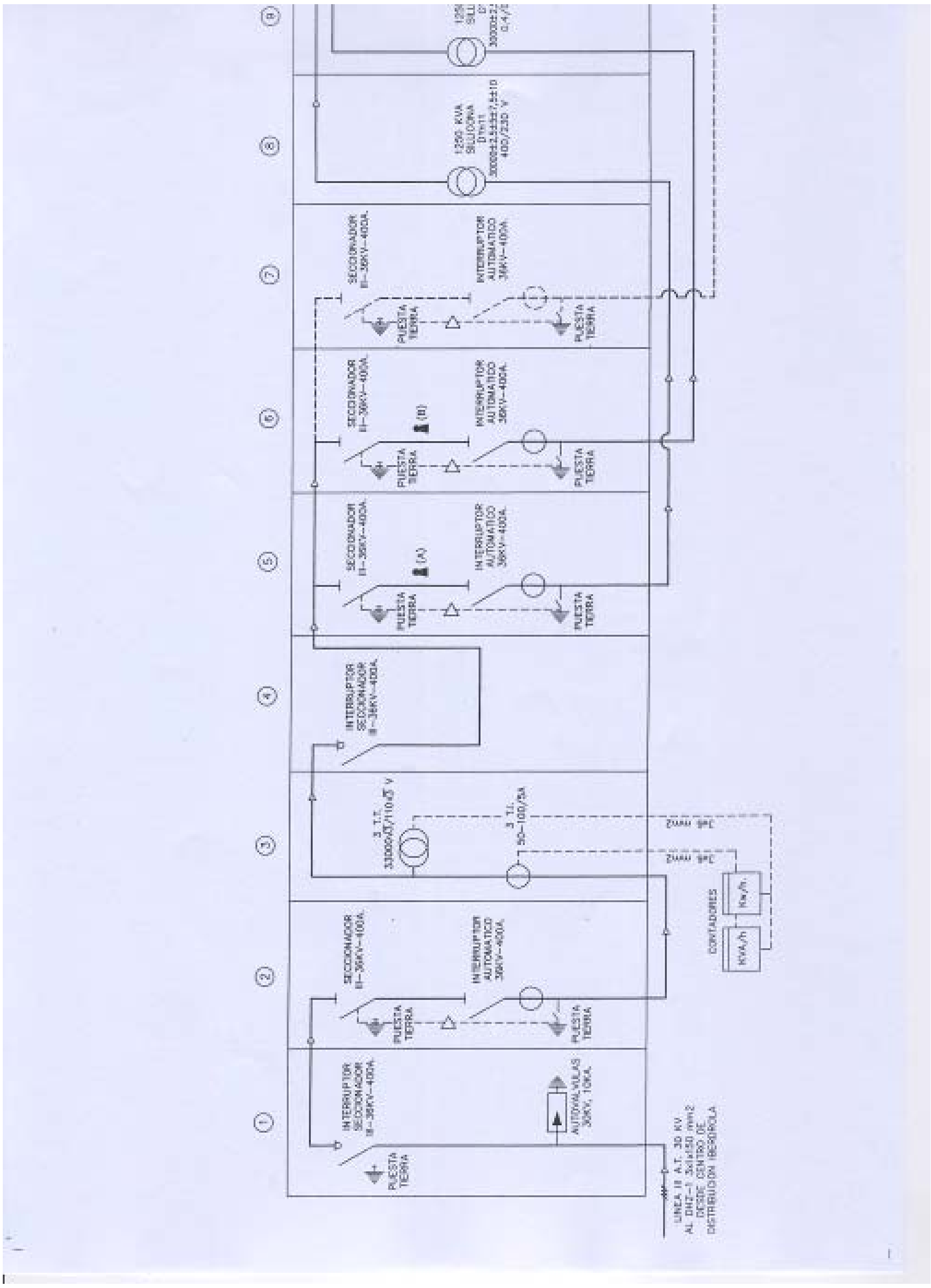

Figure 2-2: Single line transformation centre diagram

3. DG Laboratory components

LABEIN’s DG Laboratory components cover:

- Generation
- Storage
- Load
- Network simulators (AC or DC)
- Line simulator
- Power Quality measurement and analysis

The µGrid is prepared to be connected either to the main electrical network or to be operated in an isolated mode. The DG laboratory equipment can be connected each other through a central switching board where each individual component may be connected to any of the available three phase busbar systems.

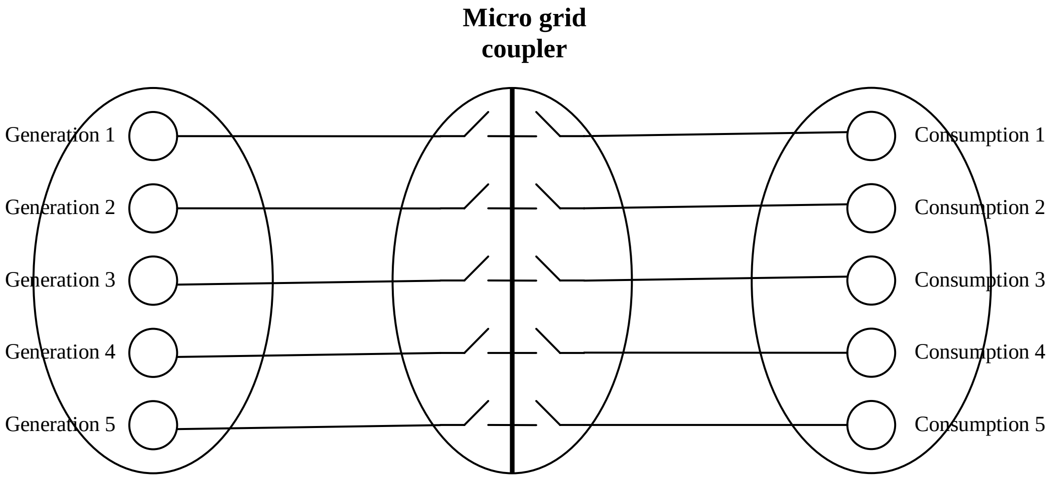

Figure 3-1: µGrid switching board

This brings the possibility for developing an amply range of different combinations for any testing.

3.1. Generation

The generation resources gathered on the experimental centre for the development and demonstration of distributed technologies of LABEIN can be divided into:

- Renewable energy based resources (wind or sun as a primary resource of energy),
- non renewable based resources (gas-oil as a primary resource of energy),
- Cogeneration (gas- oil as a primary resource of energy).

3.1.1. PV

There are three different photovoltaic installations coupled to the grid through different inverter technologies.

The available photovoltaic generation systems are:

a) A single-phase 0,6 kW peak photovoltaic installation based on thirteen UF42 modules (amorphous structure) and a SunnyBoy 1100 Inverter connecting the common DC bus to network.

Figure 3-2: Amorphous structure based photovoltaic installation

b) A single-phase 1,6 kW peak photovoltaic installation based on sixteen Isofoton I-106CR modules (mono-crystalline structure) connected to the network through a Xantrex SW 3024 Inverter. Additionally, the common DC bus is coupled to two paralleled lead acid batteries of 550 Amps·h each and 24 volts through a Xantrex C-40 regulator.

Figure 3-3: Mono-crystalline structure based photovoltaic installation

c) A three-phase 3,6 kW peak photovoltaic installation based on 24 BP SX 150 S modules (multi-crystalline structure) and three single phase SunnyBoy 1100.

Figure 3-4: Multi-crystalline structure based photovoltaic installation

3.1.2. Wind turbine

It consists on one aero generator with a nominal power of 6kW (INCLIN6000 from Bornay). The wind turbine is designed with a cut-in wind speed of 3,5 m/s and a cut-off wind speed of 12 m/s.

The wind turbine is equipped with a three blades rotor, automatic brake system by tilt up and neodymium magnet synchronous alternator. The alternator output is rectified to a DC bus and injected to the network through a three phase inverter.

The AC-DC-AC configuration allows the integration of an intermediate stage between both AC sides to investigate the MPPT following.

Figure 3-5: Wind turbine installation

3.1.3. Diesel generator

Upon the non renewable energy sources, there are two diesel generators of 55kW each. Both of them are capable for operate, either on an autonomous mode (as a pure voltage source mastering an islanded mode) or as a whole controllable unit (current, voltage or power) through a reprogrammable AC to AC converter based on a rectifier - inverter group. Without the AC/AC converter the diesel units only support the islanded mode.

Each diesel generator is composed by a John Deere 4039 TF008 motor coupled to a LEROY SOMER LSA 43.2 L6 synchronous generator (400V, 50 Hz, 63 kVA).

Figure 3-6: Diesel motor

On the UPS mode, the diesel generator is, at any time, prepared to adapt the generation to the connected consumption. Thereby, a droop control is inherent to its electromechanical controller which regulates the output frequency between 50 and 52 Hz depending if it is operating on nominal ratings (50Hz) or without load (52Hz).

When coupled through the AC/AC converter, the whole energy is stored in an intermediate DC stage, and a four quadrant inverter regulates the active and reactive power to be absorbed or delivered. This inverter operates as voltage source or as current source, in any case, within the nominal limits of the inverter (inverter switching frequency up to 20 kHz, filter cut off frequency of 1kHz). The control of the inverter can be easily modified to test whatever algorithm (harmonics control, inverter synchronization, QoS improvement…)

3.1.4. Micro turbine

The Micro turbine (Magnetek EG-50 -50 kW) system is made up of two main parts, the turbine generator and the AC-AC converter. The turbine is supplied with liquid fuel (gas-oil) and rotates at up to 60.000 rpm. The generator’s output is a 380 Vac 400 Hz 3-phase voltage which represents the input of the subsequent stage of the AC/AC converter. The AC/AC converter generates a voltage of 380 Vac 50 Hz.

Although the micro turbine is designed to be an efficient device when electricity generation and heat production are combined, the available unit has not a heat recovering system installed so far.

The AC/AC converter is prepared to operate in autonomous mode (voltage source) and in islanded mode (voltage source).

3.2. Storage

3.2.1. Flywheel

The flywheel is an uninterruptible power supply system based on the mechanical energy of a rotatory mass. It reaches full charge at 7.700 rpm (less than 150 seconds recharge). From 4.000 rpm the UPS is in normal operation regulating output voltage and supplying reactive and harmonic currents required by the load. It also provides constant power protection against surges, sags and power interruptions during 15 seconds at full capacity (250 kVA).

The overall efficiency of the flywheel (mechanical plus electrical efficiency) is 96%.

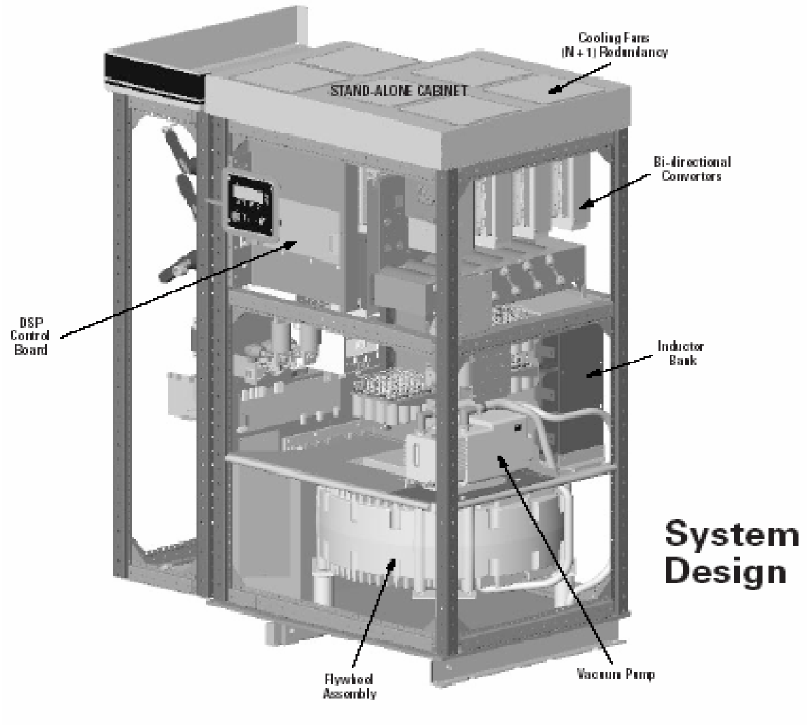

Figure 3-7: Flywheel system design

The connection scheme to the flywheel is showed at Figure 3-8. The alternate voltage is generated through an inverter, and coupled to network once the main network has been isolated to discharge the stored energy. When the voltage is recovered to its nominal values at the grid connection, the load is re-coupled to it, and the flywheel starts the recharging process.

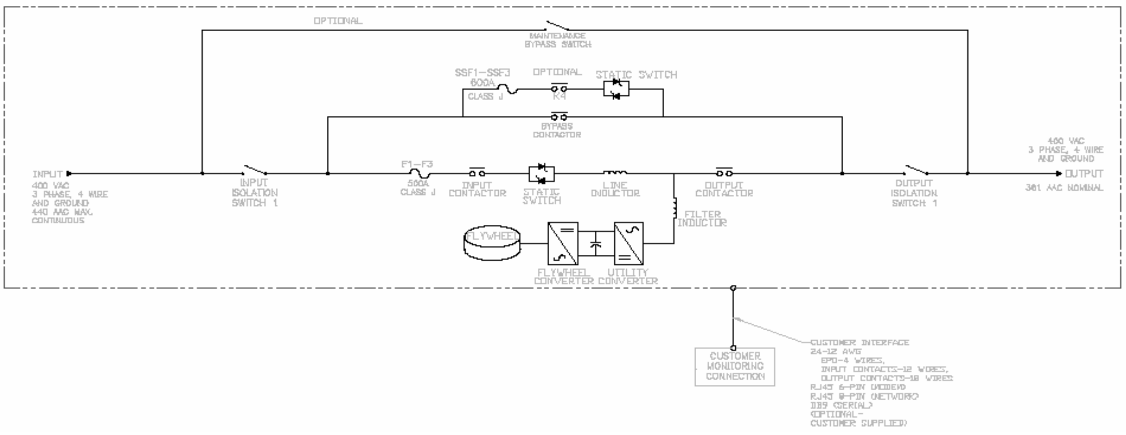

Figure 3-8: Flywheel connection scheme

3.2.2. Batteries bank

a) 1120 Ah Lead - Battery Bank

Through a DC bus of 24 Volts, this battery is connected to the photovoltaic generation (see chapter 3.1.1 a) -1,6kW mono-crystalline structure). A C-40 of Xantrex controls its state of charge, and a Xantrex SW 3024 couples the entire system to network (single-phase coupling).

b) 1925 Ah Lead - Battery Bank

Based on a $48V_{DC}$ bus, and coupled to the AC network (three-phase coupling) by means of three Xantrex SW 3048 inverters. The flow of energy through the inverter is controlled in order to regulate the voltage of the batteries, so it can be programmed to absorb energy from network in certain periods of the day, and give it back when so decided.

3.2.3. Ultra capacitor

UPS based on ultra capacitors, with single phase connection to network. A 48 Volts DC bus is supported by 8 (two parallel sets of four series connected ultra capacitors) ultra capacitances of 45,000 F. The energy stored at each one is 360 KJ. The system is able to supply the full load (5kW) for about 6.5 minutes.

Figure 3-9: Ultra capacitors bank

Depending on the power consumption, the output voltage of the ultra capacitor back varies as showed on Figure 3-10.

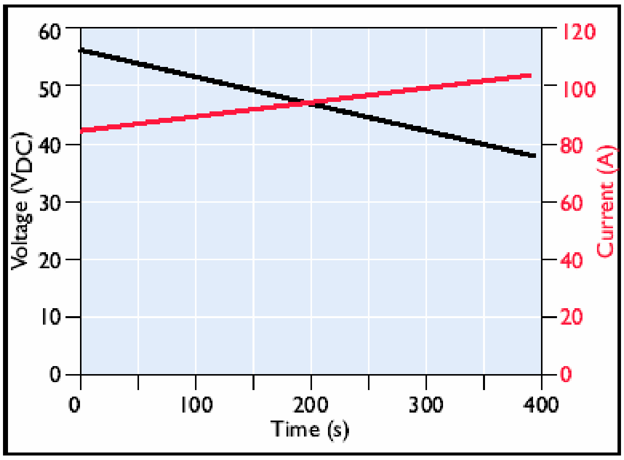

Figure 3-10: Ultra capacitors Time to Voltage and Current characteristics

The ultra capacitors are connected to network as showed on Figure 3-11, through a commercial UPS (Accratech U91-5K) and two different modules controlling the charge and discharge of the stored energy.

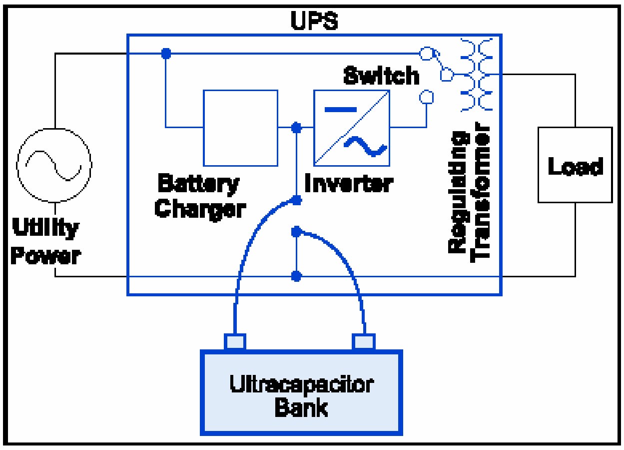

Figure 3-11: Ultra capacitor connection

3.3. Load

a) Resistive load bank (AVTRON K595)

Three phase connection to network with star configuration and available neutral wire. Available independent load steps: 1.25, 2.5, 5.0, 10.0, 15.0 kW.

Figure 3-12: AVTRON K595 resistive load bank

b) 2 Inductive load banks (AVTRON K599)

Three phase connection with star configuration and available neutral wire. Available independent load steps: 1.35, 2.7, 5.4, 10.8 and 16.25 kVA.

Figure 3-13: AVTRON K596 inductive load bank

c) Resistive load bank (AVTRON Millenium 150)

Three phase delta connection. . Available independent load steps: 5.0, 10.0, 10.0, 25.0, 50.0 and 50.0 kW.

Figure 3-14: AVTRON Millenium 150 resistive load

The different load banks are in process of being adapted in order to connect a hardware & software remote load controller.

3.4. Network simulators

The voltage and frequency which assures the establishment of the network for the µGrid may be obtained in several different ways:

- Provided by the main network,
- By means of generators belonging to the µGrid and participating as synchronous sources,
- By means of inverters within the µGrid operating as voltage sources,
- By networks simulators.

3.4.1. AC network simulators

Two parallel connected Pacific Power Source 3060-MS, 62.5kVA/50kW each, can provide a 3-phase voltage 228/132 Vac up to 500Hz creating an AC voltage and frequency reference for testing purposes. Both network simulators only work as voltage source because the built in control prevents them operating as power or current source.

Figure 3-15: Pacific Power Source 3060-MS AC voltage controller

A step-up auto-transformer increases the output voltage up to 456/264 Vac. A programmable controller (UPC32) is in charge of adjusting the main parameters (voltage level between 0 and the maximum levels, frequency regulation). The injected voltage reference may be adapted to:

- Simulate voltage transients (drops, surges, sags…) with a time resolution of 2 µsec.
- Change the waveform of the voltage output (square voltage, triangular voltage…),
- Operate as an harmonic source,
- Provoke repetitive disturbances on the voltage (flicker…)

There is a limitation in the Pacific Power Sources that prevents the absorption of power, that is, the µGrid under test can not export power to the mains if the network simulators are in use.

The configuration of the two parallel connected voltage sources is showed in Figure 3-16:

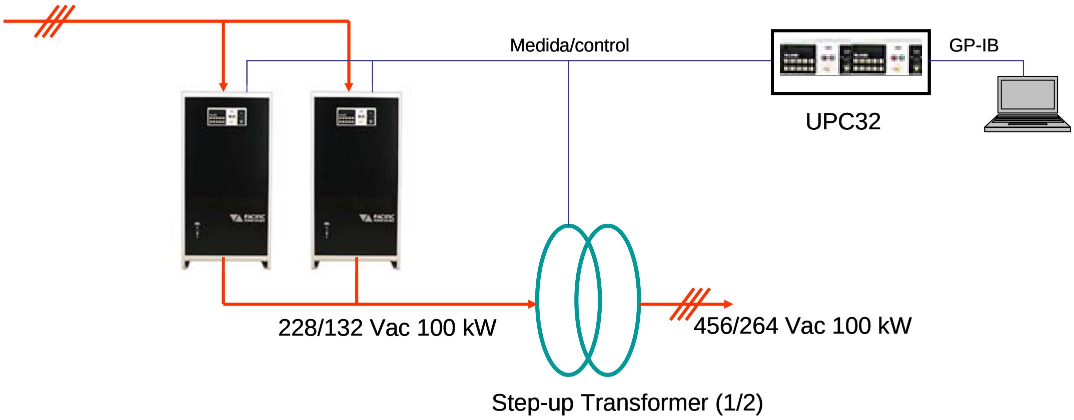

Figure 3-16: Power Source 3060-MS AC voltage controller configuration

3.4.2. DC network

A controllable DC voltage network is available within LABEIN's DG Laboratory. Thus, it can be used for testing whatever concern arising from the newly emerging DC networks. Any equipment operating with a stage of DC voltage (inverter, DC-DC converter, batteries…), can be connected for assess its operation under the test conditions.

Two different alternatives are available to generate the DC network: rectifier and inverter.

3.4.2.1. Rectifier based DC bus

A controllable rectifier which accepts a 380 Vac 3-phase voltage and provides a external-controllable (4-20 mA) output from 540 Vcc to 780 Vcc (100 A maximum).

This brings the possibility of generating a DC voltage bus with the typical harmonic distribution produced by rectifiers.

Figure 3-17: Controllable rectifier

3.4.2.2. Inverter based DC bus

Two PM 1000 PowerModules (American Superconductors Corporation) based on the inverter technology are available to generate a controllable DC voltage between 500 and 900 Vcc. The nominal power of each unit is 100kW.

These converters can operate in four quadrants on the AC side (generation- consumption of active-reactive power), which guarantees a fine control of the DC output voltage levels and minimize the impact on the AC side.

On Figure 3-18 it can be seen that the scheme which is composed of:

- AC filter to reduce the harmonic emissions,
- The PM1000 module in charge of convert the AC voltage into a DC one,
- The software controller aimed to regulate the operating point of the entire system.

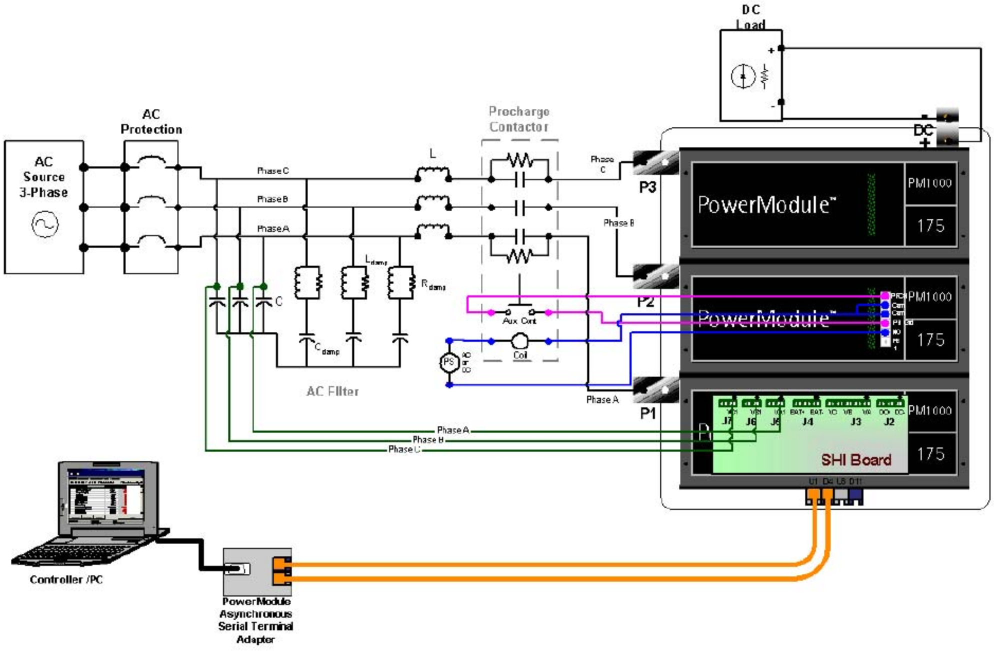

Figure 3-18: PM1000 power module configuration

3.5. Line simulator

A configurable line simulator is available at LABEIN's DG laboratory, being possible to adjust the magnitude and angle of the circuit that is supposed to be connecting the generation and the consumption.

Different ratios (R/X) can be simulated for the line impedance (7, 3, 1, 1/3, 1/7) and different penetrations ($\frac{S_{Nominal}}{S_{Short-Circuit}}$) (7,5%, 5%, 2,5%). Whatever combination of these two ratios can be established on a line within the nominal ranges of:

- Nominal voltage of 380V,
- Nominal power of 10kW.

Although the line simulator is limited to 20 Amps, it may be used to extrapolate and scale up obtained results when per unit values are in use and the contour parameters are properly chosen. A reduced scale model may be constructed adjusting line impedance, transmitted power, reference voltage and current to measure whatever impact (for instance, voltage fluctuations) in per unit terms, suitable to be generalized for the reference systems.

3.6. Islanded to & from grid connected transitions

3.7. Power Quality measurement and analysis

3.7.1. Power Quality & Energy Monitoring

DRANETZ-BMI Signature System is an integrated, web-based platform that allows users to remotely—and in real time—monitor their power systems. A Signature System incorporates multiple measuring and monitoring instruments called DataNodes reporting to a gateway/web server called an InfoNode.

The DataNode 5530 captures half-cycle RMS triggering on voltage and current, voltage and current transient triggering to 1µs, voltage and current harmonics, and interharmonics. The DataNode also can be set up to collect, trend and trigger on values from a list of hundreds of additional power quality, energy and process parameters.

The InfoNode 5500 offers a gateway to aggregate, process and view information from up to 32 DataNodes on a real-time basis, offering multiple communications paths for simultaneous access of up to eleven users. The InfoNode provides a user interface via a self-contained, password-protected web server. Protocols supported include TCP/IP, HTTP, UCA-2, and MODBUS.

3.7.2. Power Quality Analyser

LEM TOPAS 1000 is a portable Power Network Analyser for medium and low voltage networks. It measures THD, flicker, harmonics, inter-harmonics, transients, unbalance of voltages, ripple control signals. It allows also to the assessment of voltage quality as per EN50160 standard.

3.7.3. Universal Disturbance Analyzer

DRANETZ 626 G is a modularly expandable system (up to five modules can be installed) for measuring Surges, Sags, Spikes, Dropouts, DC Volts, Ac Current, Temperature, Humidity, Events, Plus Communications and Frequency Errors on DC and AC Power Lines.

4. LABEIN's µGrid

The summary overview of Labein's DG Laboratory components and its use for µGrid testing purposes is shown at Figure 4-1.

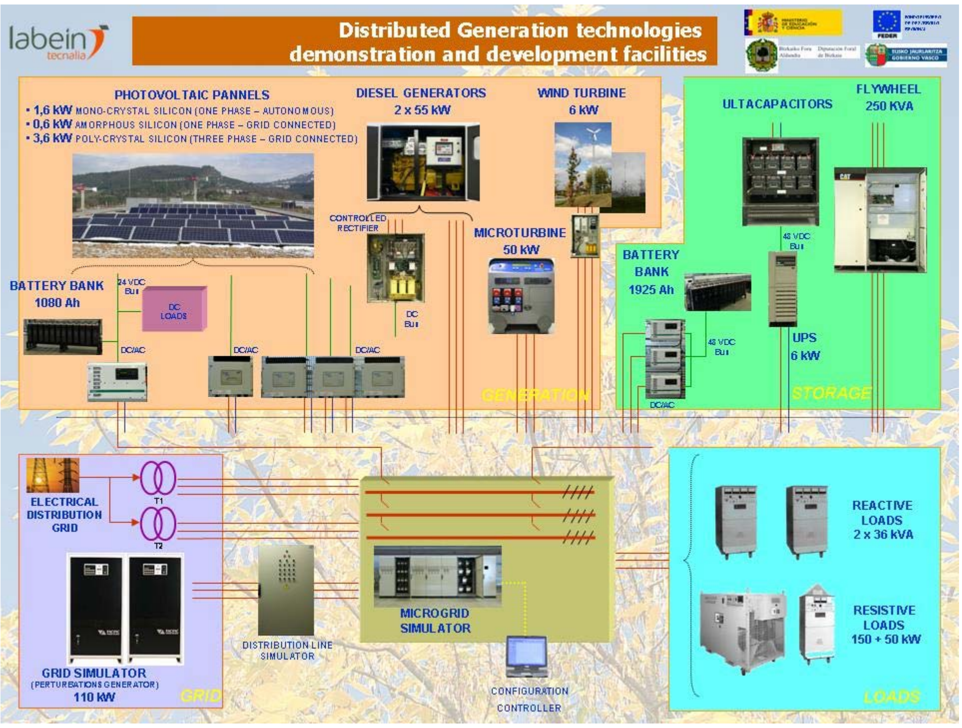

Figure 4-1: Summary of LABEIN's µGrid

It can be seen from figure, that every device can be coupled with each other through a switching board (tagged as 'Micro Grid Simulator[1]' in the figure). On this way, it is possible to reconfigure easily whatever topology in which generation, consumption and storage are connected together.

The Switching Board is characterized by:

- There exist three different three phases buses (with neutral wire) at a time,
- Any of the three buses could be connected to any other bus system,
- Any equipment of the DG laboratory may be connected to whatever bus,

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[1] The 'MicroGrid Simulator' label is misleading. The real function of this component is to act as MicroGrid Configurator allowing the formation of LV grids with different components and suitable for each test objectives. That is, enables an easy electrical connection and disconnection through a convenient interface.

- The configuration of the micro grid components is software controlled,

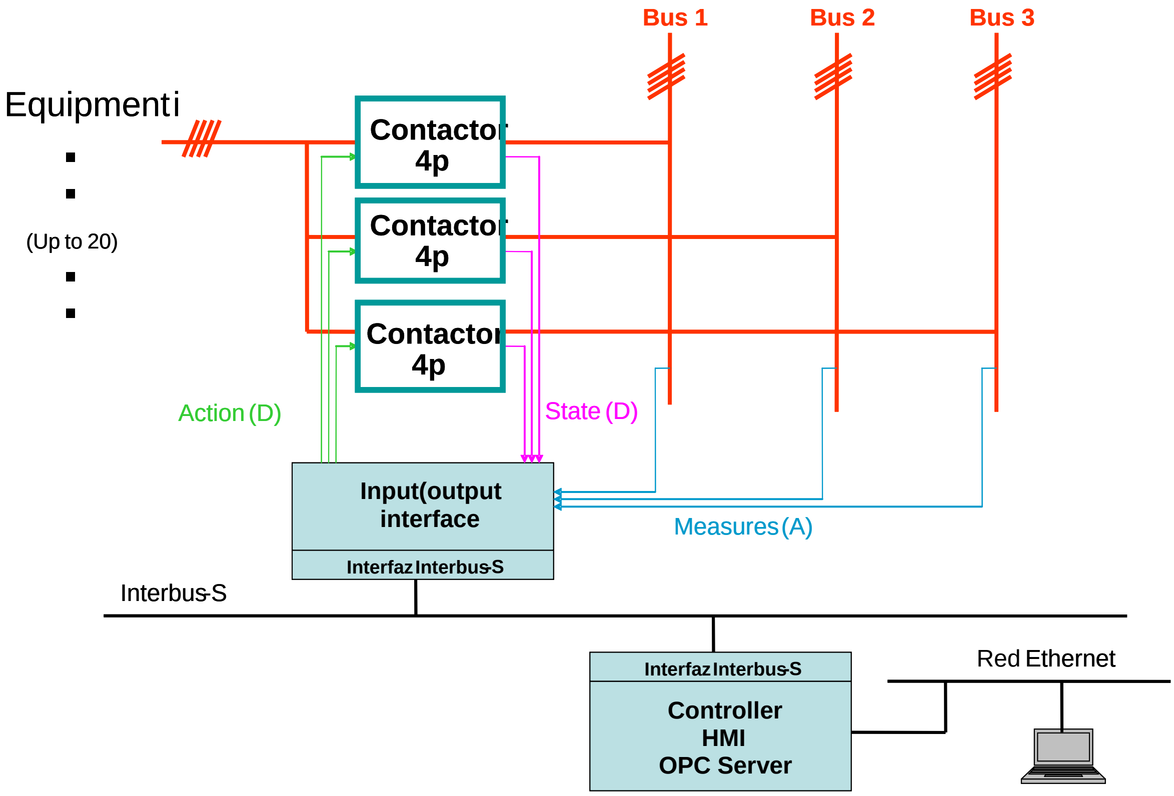

Figure 4-2: Switching board architecture

4.1. Static Switch

The available elements at the DG technologies laboratory may be connected to any of the three three-phase bus systems independently though electrically managed contactors. These contactors are intended to be operated under zero current conditions leading to a ‘fixed’ equipment topology for any conducted test.

An in-house developed static switch has been built out of of-the-self components for hardware while the switching operation is controlled from the driving board. In order to avoid any possible software problem leading to unexpected switch operations a synchro-check relay acts as master enabling the command produced from the switch control algorithm.

Figure 4-3: Static Switch

5. Test to implement

Since a significant amount of generation is expected to be connected at low voltage level networks, the effect of the lack of coordination on its power control need to be studied in detail to assure that the entire network operates within reliable margins. In this scenario, every connected resource must be capable of adjusting its point of operation within a range so as the QoS is reinforced.

Furthermore, it results interesting not only to attend to QoS issues, but also to adjust the resources connected to the network in a synchronized manner, such that economical or efficiency matters are taken into consideration.

5.1. Primary, secondary and tertiary regulation

On a µGrid scenario, two important issues are the real time generation adjustments resulting from load following and the subsequent required re-schedule of generation profiles due to economic & technical reasons.

Primary regulation is related to the automatic sharing of power amongst the participants on feeding the µGrid demand. This power sharing can be accomplished either through local control or through an external control intended to coordinate the different responses.

Once the generation-consumption balance is achieved on the basis of primary regulation an intelligent µGrid controller is foreseen as essential tool to modify the generation schedules accordingly to the new situation attending to some criteria. This stage constitutes the secondary regulation of the available generation and storage devices.

On the long term, the amount of stored energy, primary energy availability (I.e. intermittent generation forecast) should be managed properly leading to the need for tertiary regulation.

5.2. Demand management

The different demand control based approaches (demand side management, demand side bidding, demand response…) have been proved as valid alternatives to handle the generation-consumption balance.

Two approaches are aimed to be developed and tested within DG Laboratory:

- Adjust demand to certain pre-programmed curves
- Adapt demand profiles to match generation profiles, specially those coming from renewable power sources.

5.3. Grid connected / islanded transitions

Assuming that a µGrid has not been designed to operate isolated (as those aimed to remote locations where distribution network is not available) it is paramount to ensure that the transitions between the grid connected and the islanded mode of operation run as smooth as possible to avoid any transient disturbing connected consumers.

MoreMicroGrids

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Contents

Index of figures

1. Introduction

This document describes the different tests conducted on the static switch deployed to the DG Laboratory.

The report outlines the static switch architecture and components and then testing is separated under two separate chapters. The first one is devoted to basic functionality (connection / disconnection) testing under different scenarios and the second one concentrates on synchronization cases.

2. Static Switch Architecture

The architecture of the static switch is shown at Figure 2-1. The static switch is deployed to the main switching board, with each side of the switch connected directly to one of the three phase busbar systems. The switch is equipped with one bypass implemented with one contactor.

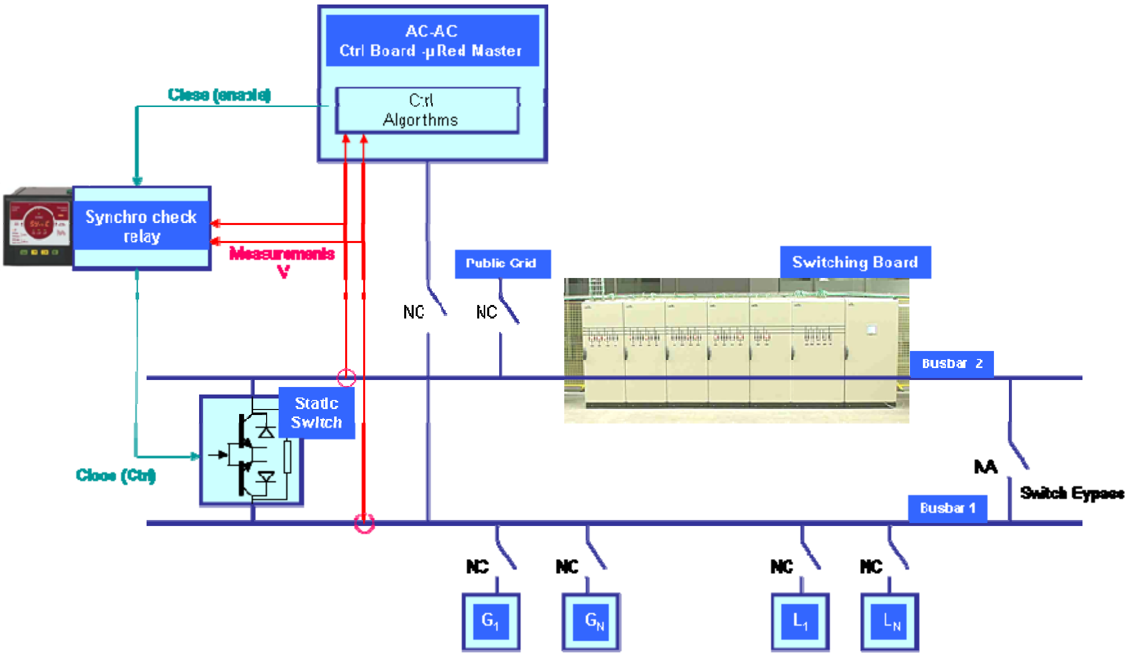

Figure 2-1: Architecture of the static switch

For testing purposes, the public network is connected to one of busbar systems (busbar 1), the required µGrid components to other (busbar 2) and the static switch operating between both busbars.

The static switch is hardware is composed by a commercial power electronics board (W3C - thyristor standard stack). Both neutrals are solidly connected and there is no physical separation along the tests.

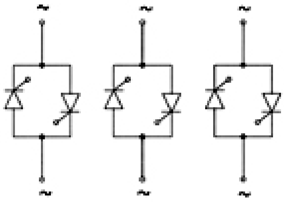

Figure 2-2: Power board layout

The thyristor control is based on a commercial zero crossing control. This sort of control measures the voltage in both sides of the thyristor and activates it when the voltage signal is positive after the zero cross, then the thyristor is active along all the semi-cycle duration. As consequence and giving the components layout, the board behaves as a switch when enabled and this is exactly the desired functionality. Other controls are also possible (depending on the phase angle, etc.) but the overall design is more complex and produce little added value for the intended aim.

Figure 2-3: Deployment of the static switch inside the switching board

The main control of the static switch is installed into the control board of one of the AC/AC converter transforming this unit into the µGrid master guiding the synchronization process. Thus, it is responsible for measuring the main grid and µGrid voltages and managing the re-connection process.

The main control signal is enabled or disabled by a commercial synchro check relay configured with standard set points. This second element is in charge of avoid any malfunction or risk testing separately voltages on both sides of the switch and ensuring that the voltage in both sides is close enough to be the acceptable.

The synchro checker is configured with:

- Minimum mains voltage: Ensures the main grid is stable.
- Maximum voltage difference – Module (%ΔV)
- Maximum voltage difference – Frequency (%Δf)
- Programmable delay timer.
- Maximum ROCOF (Rate of Change of Frequency) function.

Figure 2-4: Synchro check (top left)

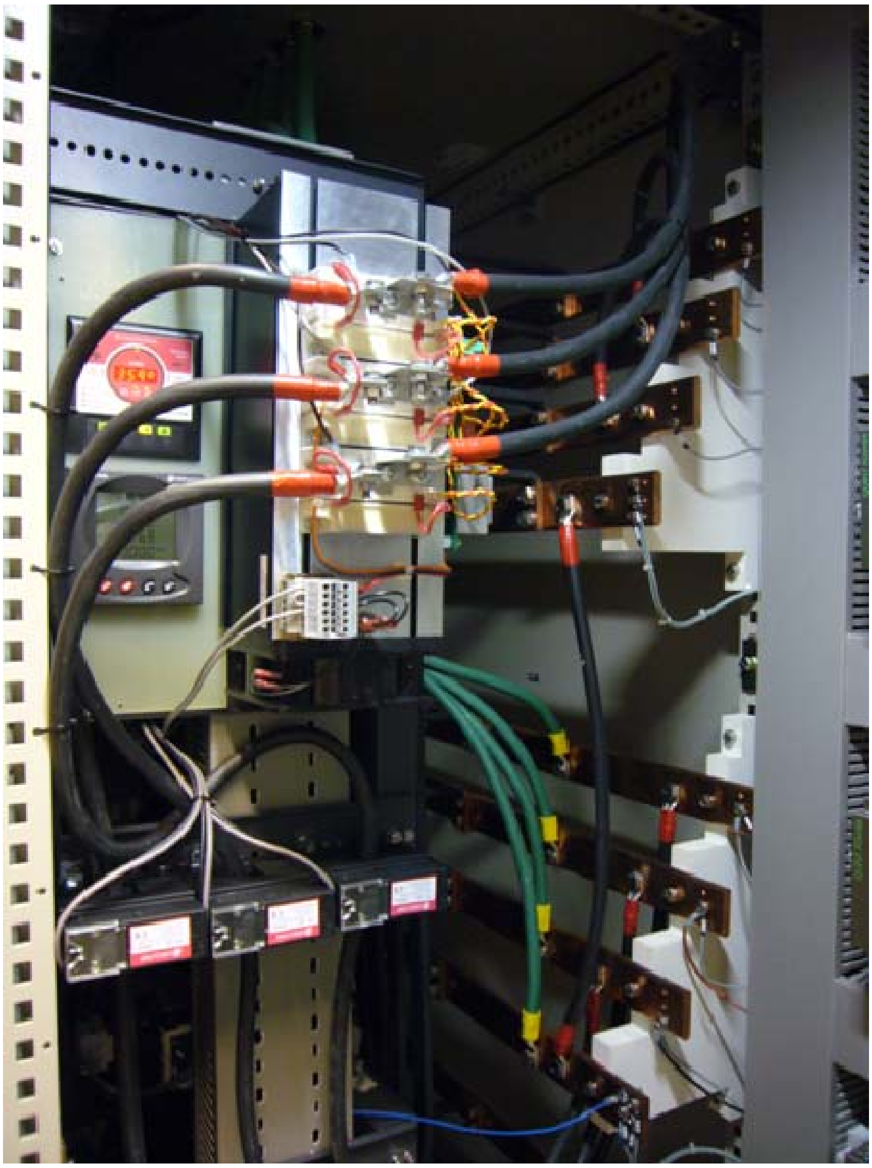

Figure 2-5: Detail of the static switch

3. Testing – Basic functionality

3.1. Four Quadrant power flow

The proper behaviour and functioning of the power and the control board of the static switch is ensured testing the response under any power flow combination: P & Q positive or negative.

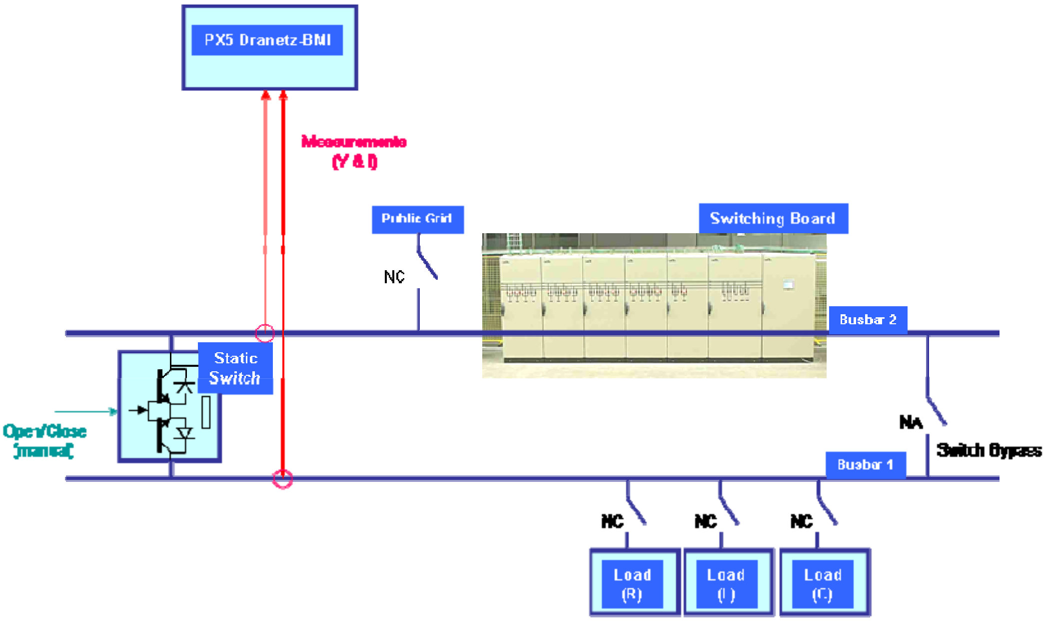

Figure 3-1: Layout and components for four quadrant tests (P>0)

The Figure 3-1 details the components and layout used for this testing. The public grid is connected to one busbar system, the required µGrid component to a second busbar system and the static switch is commanded manually. The µGrid component varies depending on the required energy flow: resistive, inductive and capacitive loads are used for P & Q scenarios where power is injected into the µGrid and controllable generators for scenarios where power is reversed.

The power system parameters are measured and recorded using a PX5 Dranetz-BMI power monitoring instrument. There are 4 independent voltage channels and 4 current channels. So, when both sides are targeted in the test two phase-phase voltages of one side are taken and their corresponding two in the other side of the switch; in contrast, if only one side is important then the three voltages of such side are considered. The measurements of the current are managed in the same way, taking either two measurements on each side either the three phases of one side.

The testing is intended to assess the static switch performance and the behaviour of the islanded system (whether it survives the transition) is irrelevant.

3.1.1. Inflow with resistive load (P > 0 & Q = 0)

The test consists on connecting a load of 11.1 kW as µGrid component so the energy flows into it from the mains.

The Figure 3-2 shows the time diagram of the process, fist the switch is open and then it is closed so the main network feeds the connected load; a few seconds later the switch is commanded to open again.

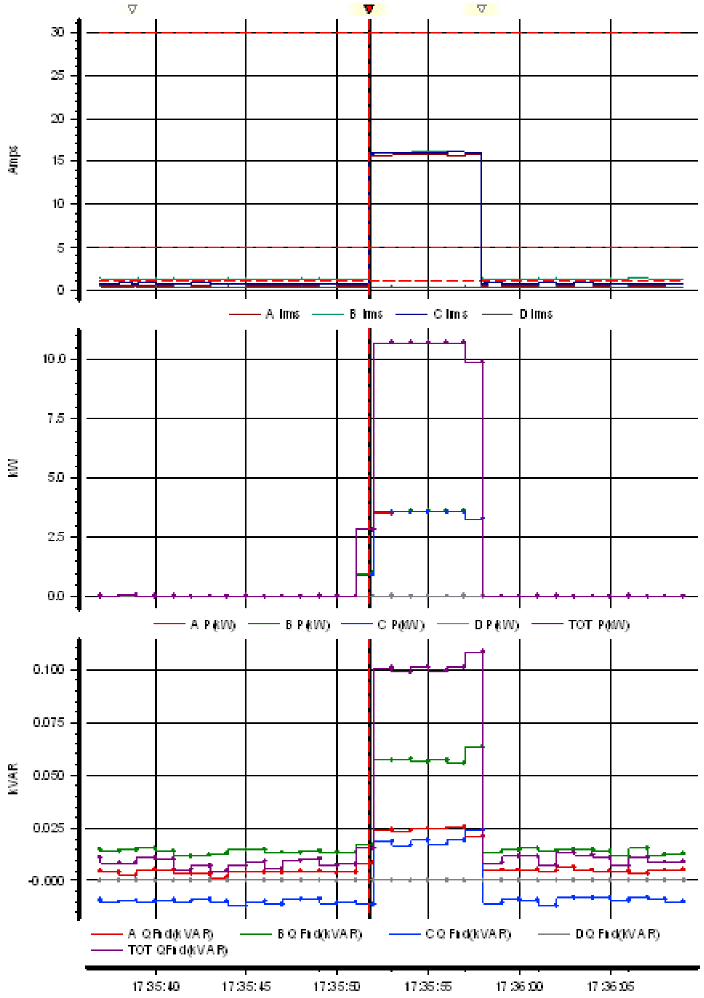

Figure 3-2: Time diagram for a connection & disconnection under resistive load

The Figure 3-3 shows the voltage and current measurements during the switch connection. It can be observed that, as soon as the voltage crosses zero on switch phase becomes active and power & current flows. For any of the phases, the feed load is resistive so the measured current is in phase with the corresponding voltage.

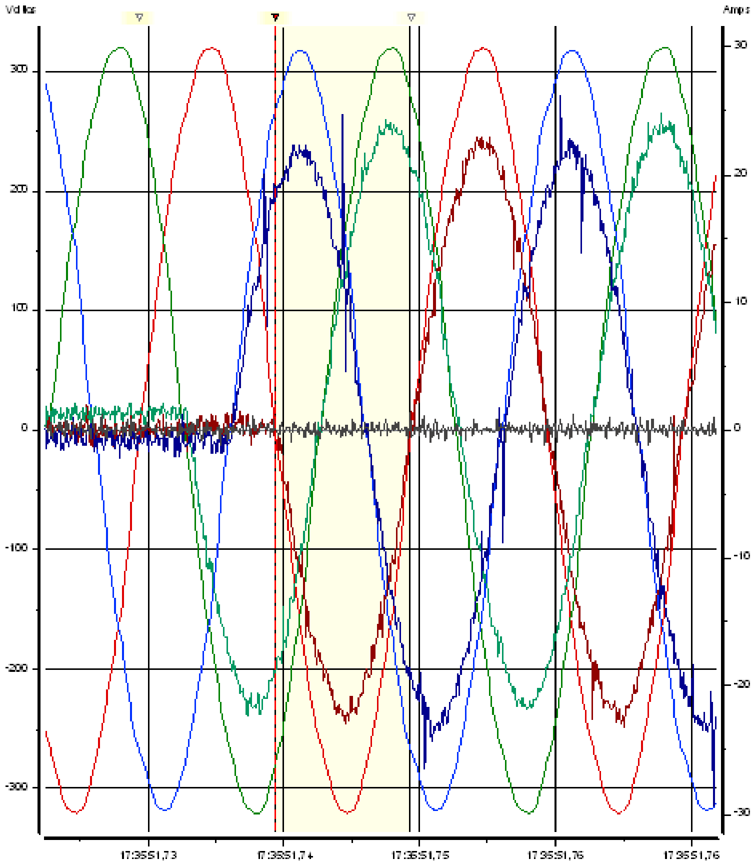

Figure 3-3: V and I measurements (one side): Connection # Resistive load

In contrast, Figure 3-4 details the measures during the disconnection of the µGrid, each switch phase opens when the voltage crosses zero and the current in that phase becomes null.

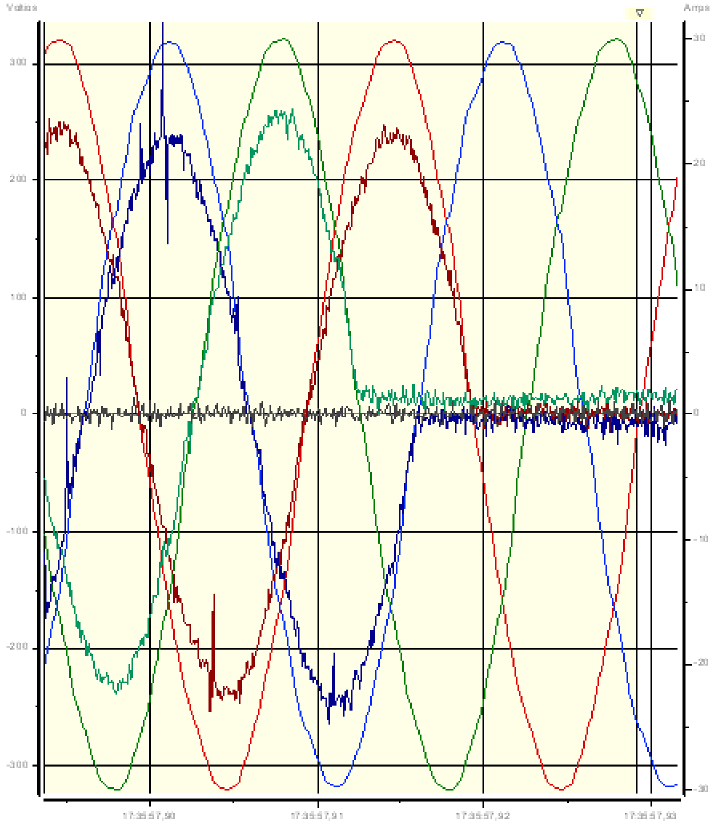

Figure 3-4: V and I measurements (one side): Disconnection # Resistive load

The Figure 3-5 represents the same connection process as it appears in Figure 3-3 but, instead of plotting the measurements taken at one side of the switch, the measurements of voltages at both sides are combined while the current measurements are at one side. After the connection, the two plots of the voltage (grid side of the switch and µGrid side) are overlapped because the negligible voltage drop along the switch. At the connection instant there is a slight difference in voltages while the voltage is being established (for less than 1/8 of the cycle) but currents do not show any significant distortion.

The apparent difference in phase is due to the triangle-star combination, currents are phase-neutral but voltages are phase-phase.

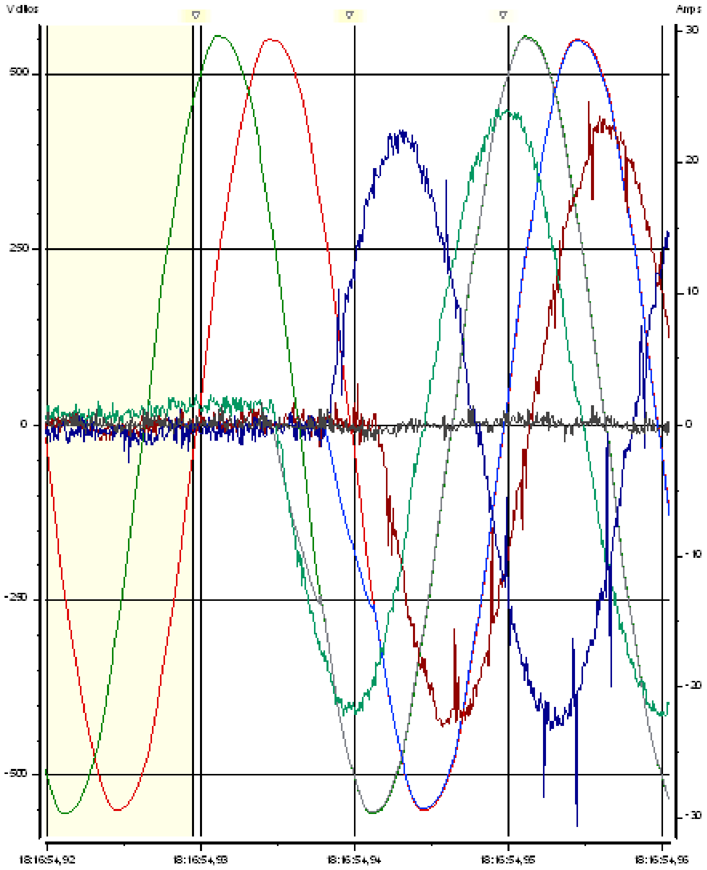

Figure 3-5: V (both sides) and I measurements: Connection # Resistive load

The Figure 3-6 summarizes the disconnection process for a resistive load. As during the connection process, immediately after disconnection process there is some residual voltage that converges rapidly to the expected null value while currents seem to be cut away faster.

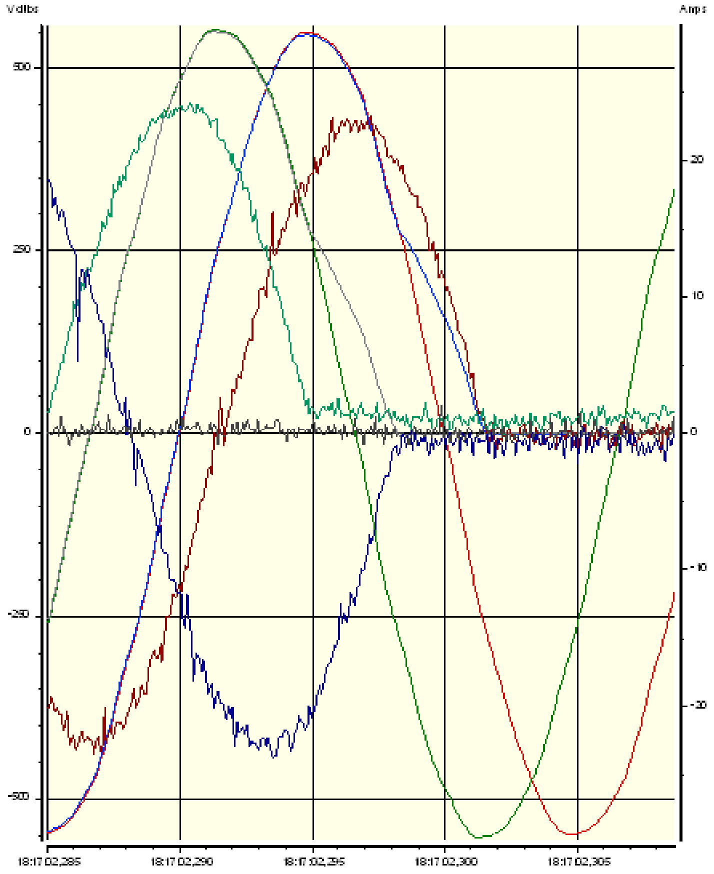

Figure 3-6: V (both sides) and I measurements: Disconnection # Resistive load

3.1.2. Inflow with inductive load (P = 0 & Q > 0)

The test consists on connecting and disconnecting an inductive load of 10 kVAr as µGrid component, the energy flows into it from the mains with the conventional sign criteria. The test timing appears at Figure 3-7.

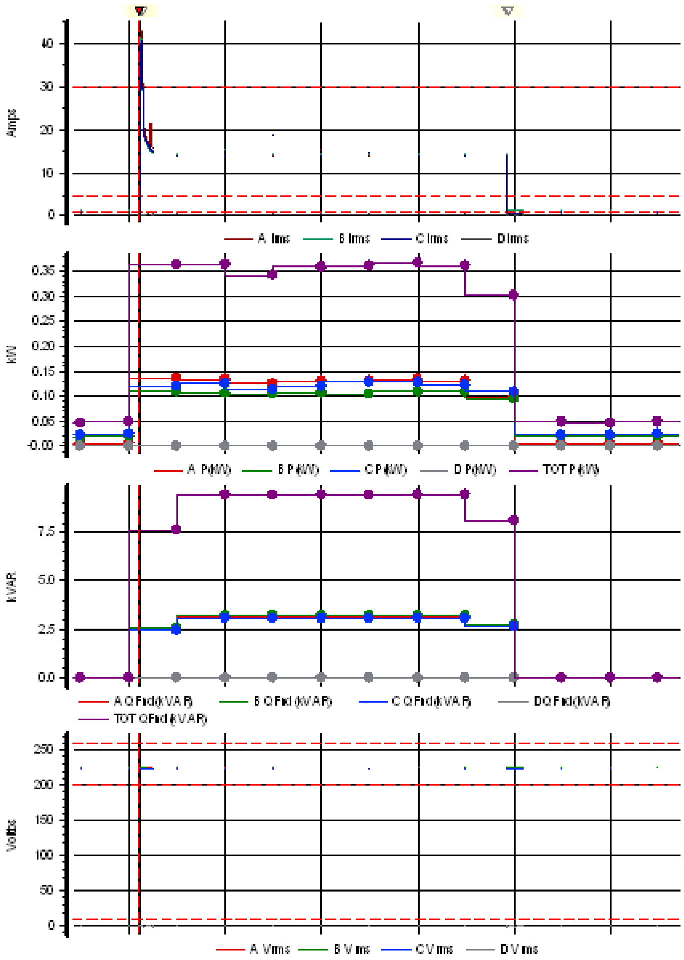

Figure 3-7: Time diagram for a connection & disconnection under inductive load

The Figure 3-8 depicts the three voltages and currents on one side of the switch at the connection event. At the instant the voltage crosses zero the switch activates and currents start flowing. Due to the characteristics of the inductive load there is a transient phase lasting about 8 – 10 cycles (it depends on the damping parameters of the configured circuit) until the steady state is reached.

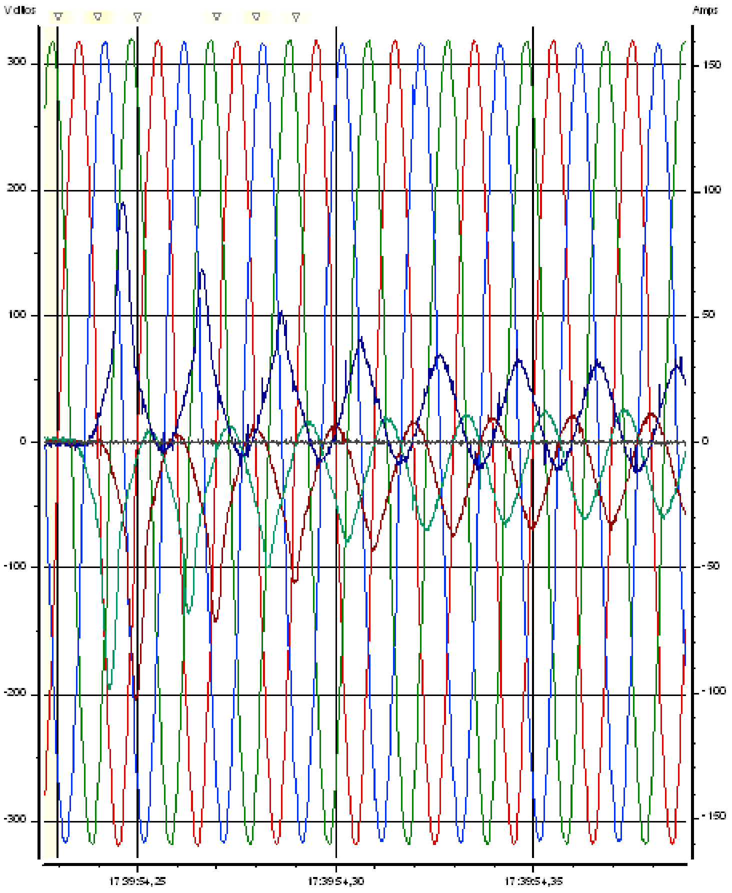

Figure 3-8: V and I measurements: Connection # Inductive load

In Figure 3-9 it is drawn the set of three voltages and currents during the disconnection of the switch. Once the open signal has been sent, when the voltage crosses zero the control board does no fire the thyristors but they continue active until the current reaches zero. The current lags the voltage by 90º electrical degrees and therefore is some sort of delay due to the still flowing current. As the three currents cross zero and the control board does not fire the components of the power electronics board the switch remains in open position.

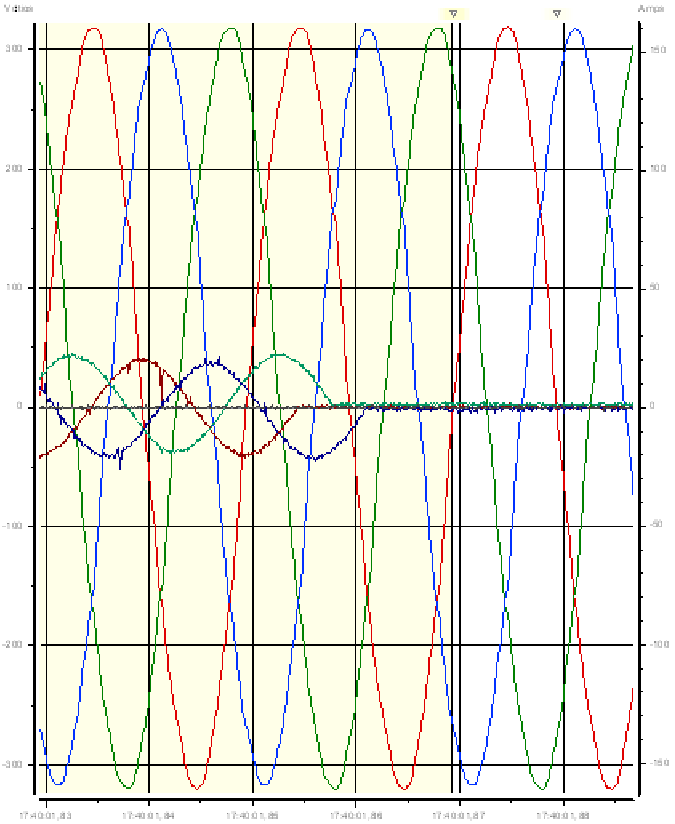

Figure 3-9: V and I measurements: Disconnection # Inductive load

In Figure 3-10 the voltages at both sides of the switch and the current across it during the connection establishment are reproduced. As in the case of the resistive load there is a small transient in the voltages at the µGrid side of the switch. The transient in currents takes longer as seen at Figure 3-8.

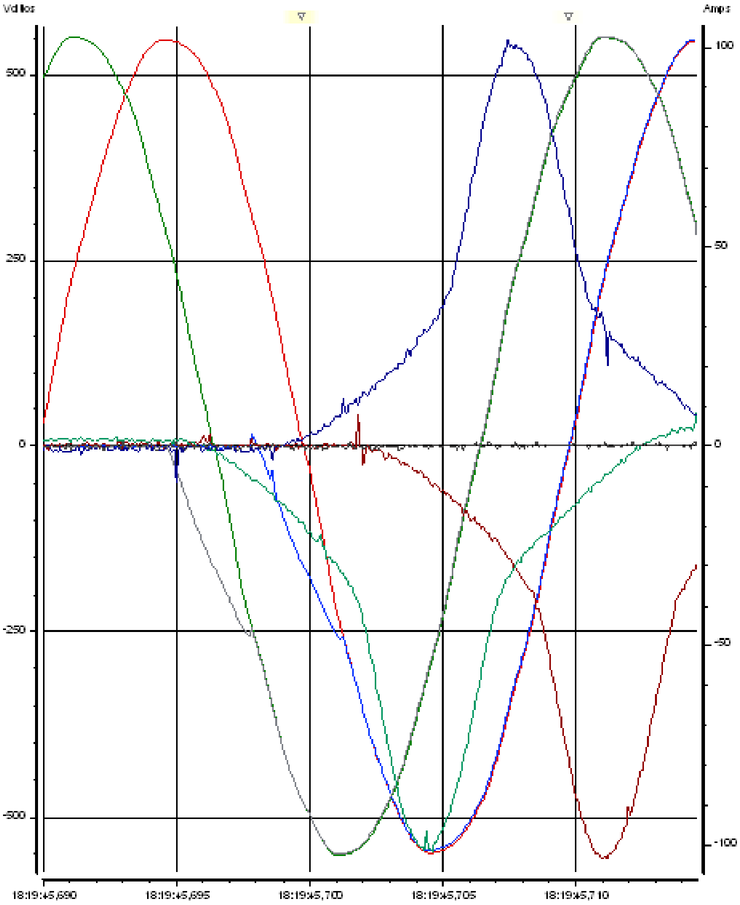

Figure 3-10: V (both sides) and I measurements: Connection # Inductive load

In Figure 3-11 the voltages at both sides of the switch and the current across it during the disconnection. The current across the switch is interrupted immediately after the zero cross leading to a fast voltage transient (taking about 1/12 of a cycle) at the µGrid side of the breaker. As two phase-phase voltages are represented, the three transients are caught by PQ monitoring device.

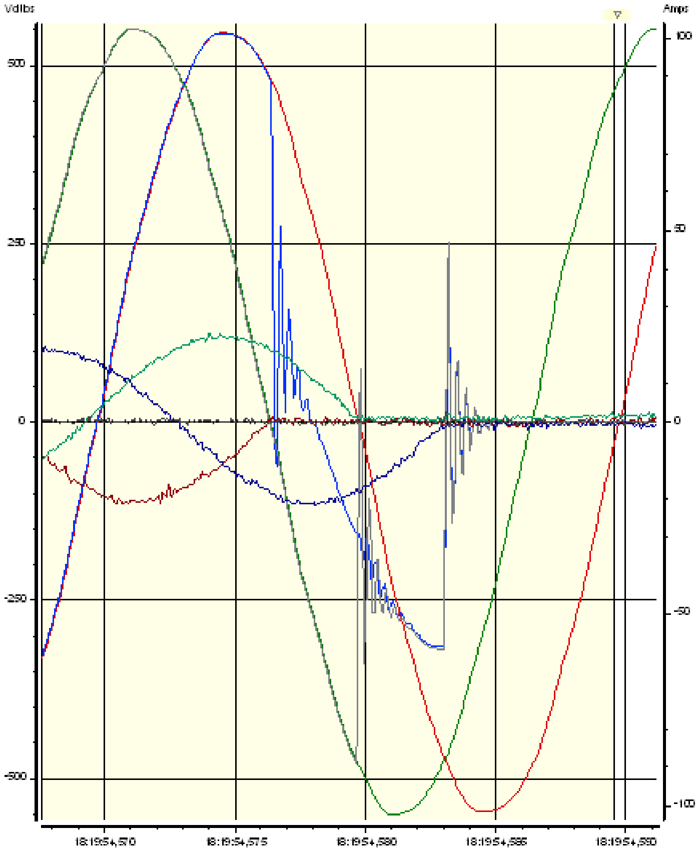

Figure 3-11: V (both sides) and I measurements: Disconnection # Inductive load

3.1.3. Inflow with capacitive load (P = 0 & Q < 0)

The considered scenario consists on a µGrid exporting reactive power into the mains. A capacitive load of 7.5 kVAr is connected and disconnected with the static switch following the timings of Figure 3-12.

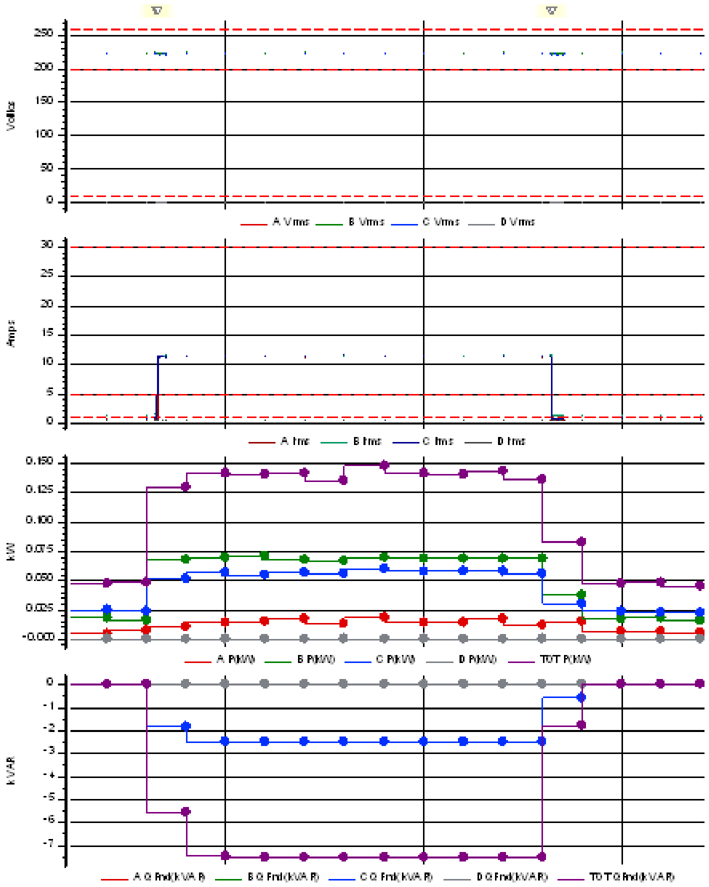

Figure 3-12: Time diagram for a connection & disconnection under capacitive load

At Figure 3-13 the three voltages and currents at the main grid side of the switch during the connection transition for feeding a capacitive load are shown. As each phase voltage crosses zero the current starts flowing with the expected signal.

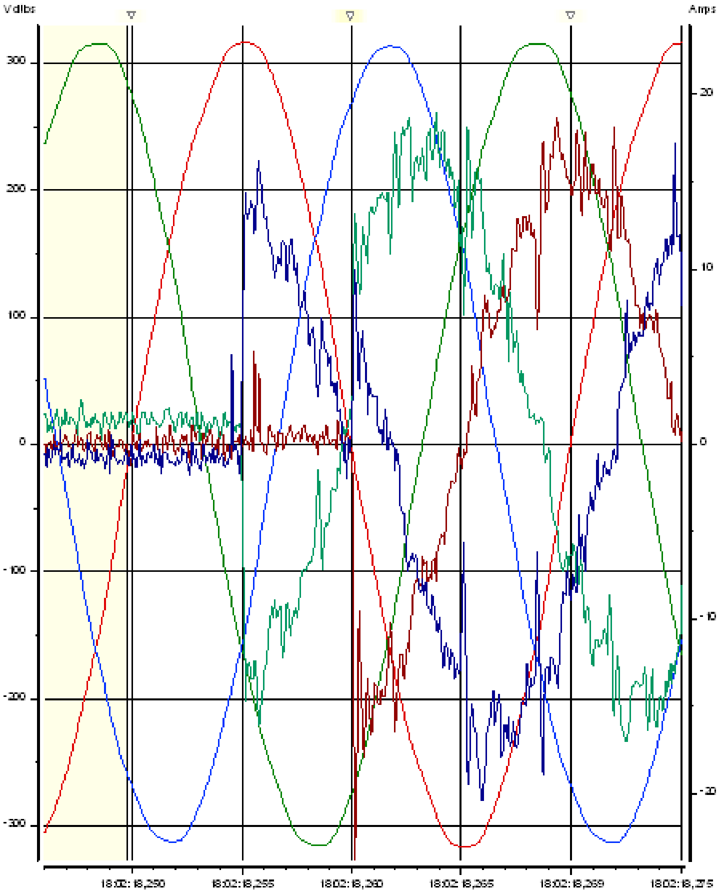

Figure 3-13: V and I measurements: Connection # Capacitive load

In a similar way, the same parameters during the disconnection of the capacitive load are drawn at Figure 3-14.

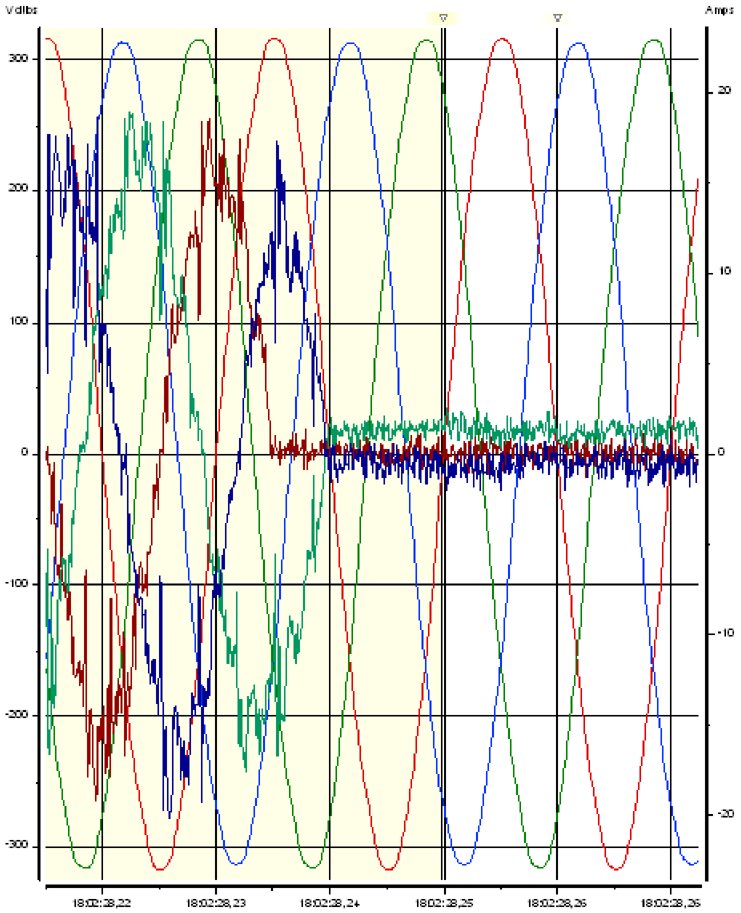

Figure 3-14: V and I measurements: Disconnection # Capacitive load

The Figure 3-15 details the behaviour of the voltage, measured at both sides of the switch, and the three phase currents across it during the connection of a capacitive load. The first phase in closing has the same voltage in both sides immediately but there is some small delay in the second one.

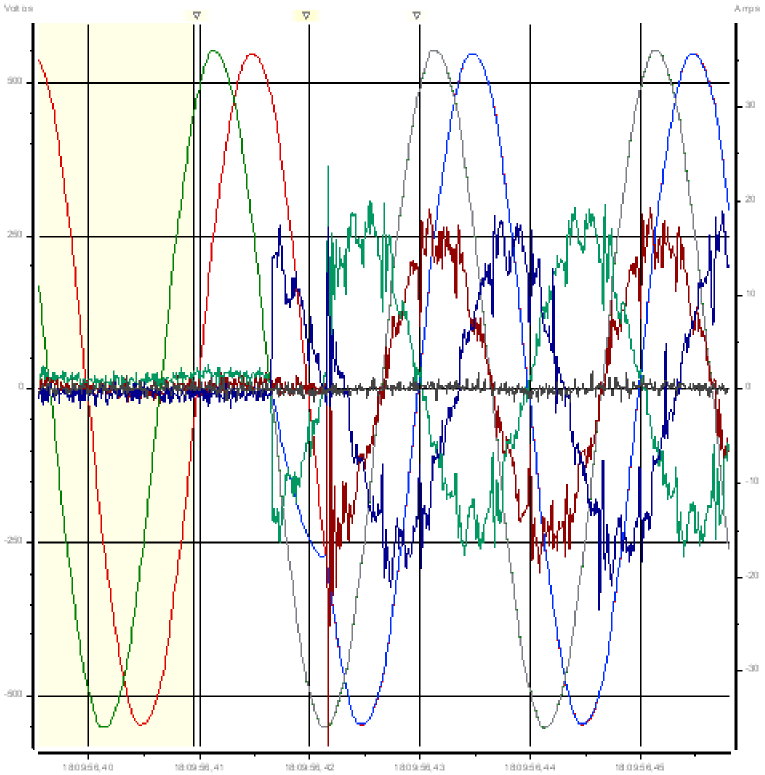

Figure 3-15: V (both sides) and I measurements: Connection # Capacitive load

The Figure 3-16 shows the opposite process of opening the static breaker. Up to the instant in which the current flow is interrupted the voltages at both sides of the switch are virtually the same but once the flow is interrupted the phase-phase voltage at the µGrid side is maintained with the logical decay due to the discharge of the capacitors.

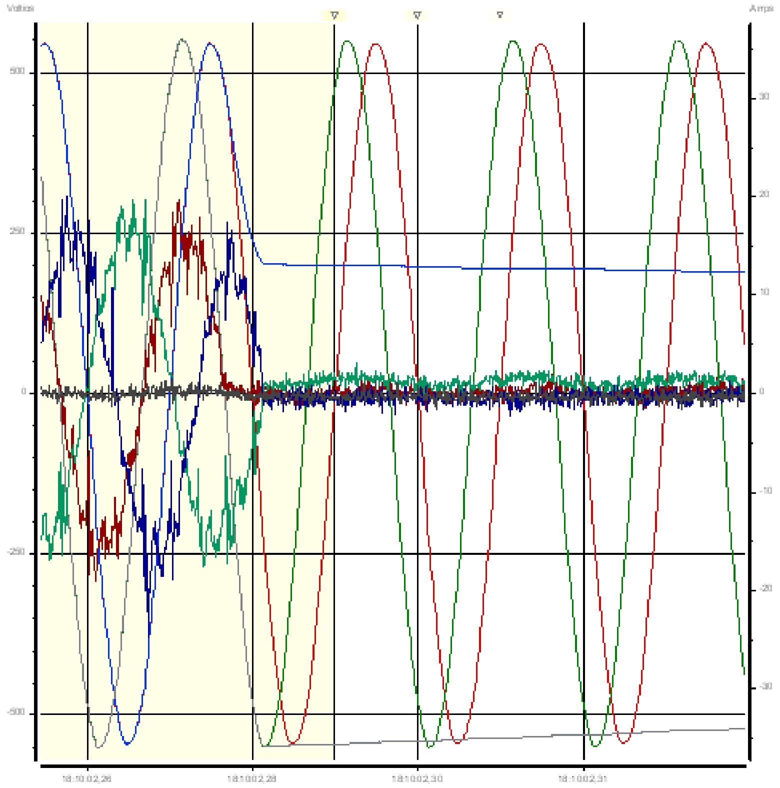

Figure 3-16: V (both sides) and I measurements: Disconnection # Capacitive load

3.1.4. Inflow with capacitive load (P = 0 & Q < 0)

The considered scenario consists on a µGrid exporting active power into the mains. A diesel unit interfaced with an AC/AC converter is connected in the µGrid side. This AC/AC unit is able to change between islanded and grid connected modes automatically.

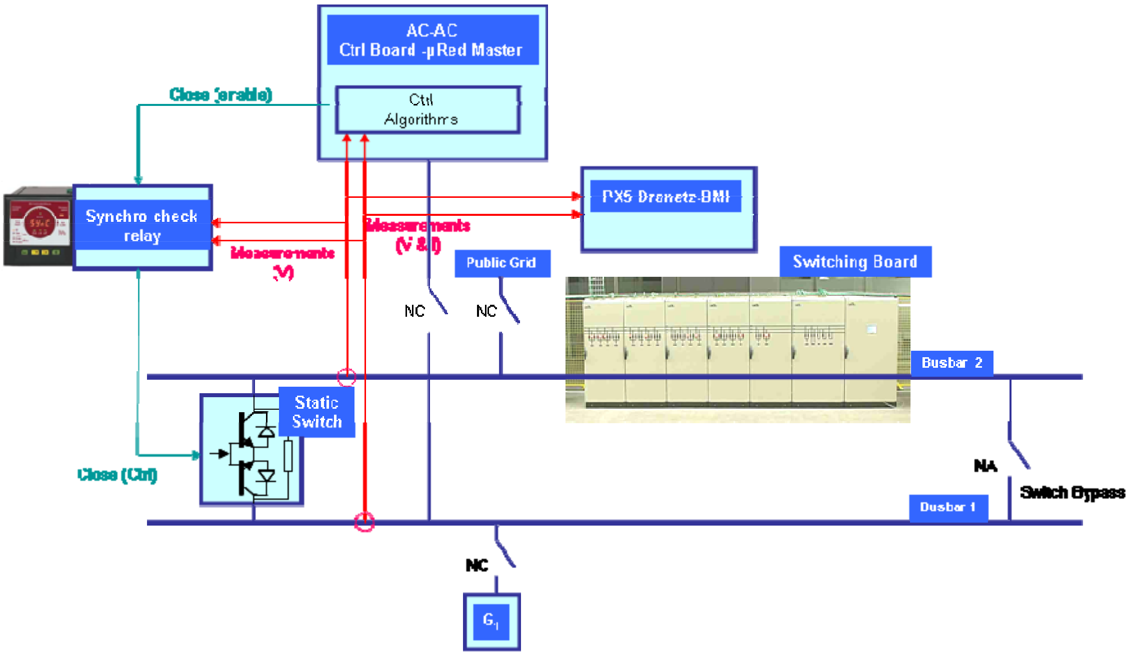

Figure 3-17: Layout and components for four quadrant tests (P<0)

It is important to note that it is difficult to test the connection because when the connection is established the grid forming unit synchronises to the external reference and it is engineered to inject no power. The tests with active power networks are documented at later chapters.

The main results are shown at Figure 3-18 and Figure 3-19. The first one details a couple of cycles while the second one extends the reported period another two cycles. At it could be expected because the static switch is symmetrical, there is not any difference in its behaviour related to whether the flow goes in one direction or the other.

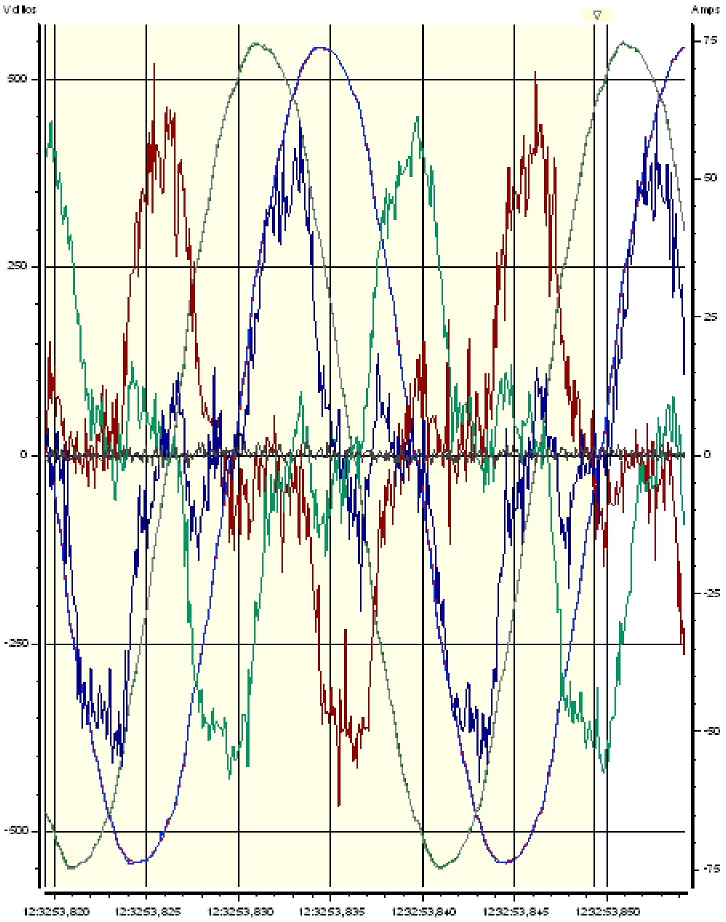

Figure 3-18: V (both sides) and I measurements: Disconnection # Export power (I)

At the disconnection of the switch the µGrid is configured to export 20 kW of power with the AC/AC converter in current source mode. While the switch is activated, the voltages in both sides are the same and when the breaker is operated to open, the inverter control detects the islanded operation and trips the unit after 3 cycles.

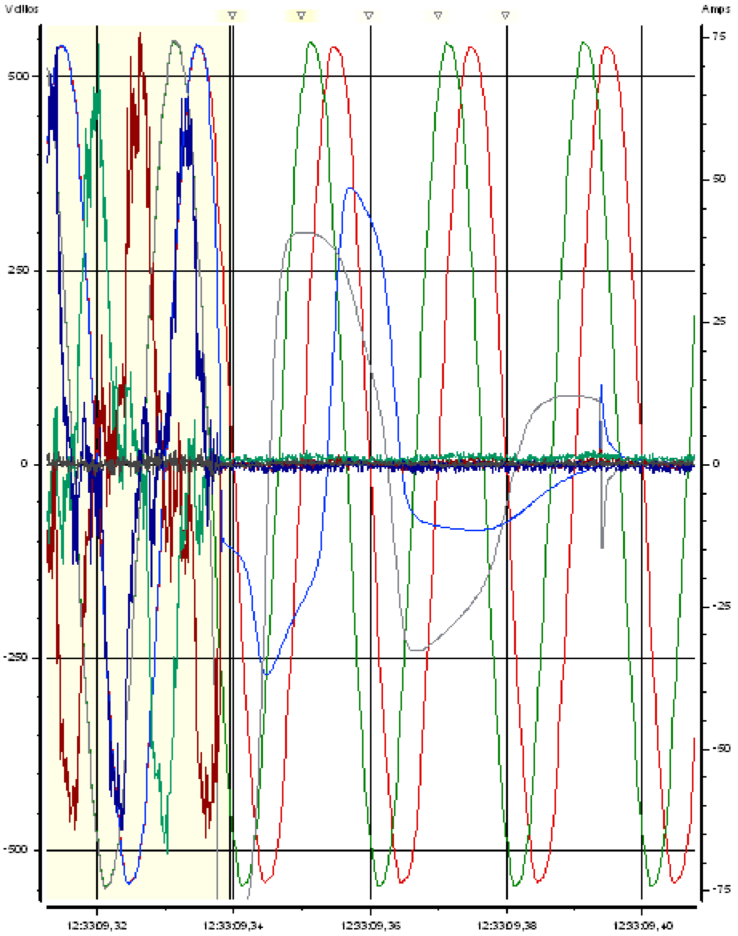

Figure 3-19: V (both sides) and I measurements: Disconnection # Export power (II)

3.2. Connection & disconnection delay

The static switch is activated with a 12 volts signal from control board. The test is intended to identify the expected delay in the switching operation due to the static breaker electronics. Obviously the delay is different for each of the phases because of the system dynamics and its characteristics. The proper behaviour and functioning of the power and the control board of the static switch is ensured testing the response under any power flow combination: P & Q positive or negative.

3.2.1. Resistive load

The test tracks the breaker control signal, the three voltages and the three currents of the switch. As it is observed at Figure 3-20 there is a lap of 9.664ms for phase A and 16.313 ms for phase C between the switching command and the effective delivery when feeding a resistive load.

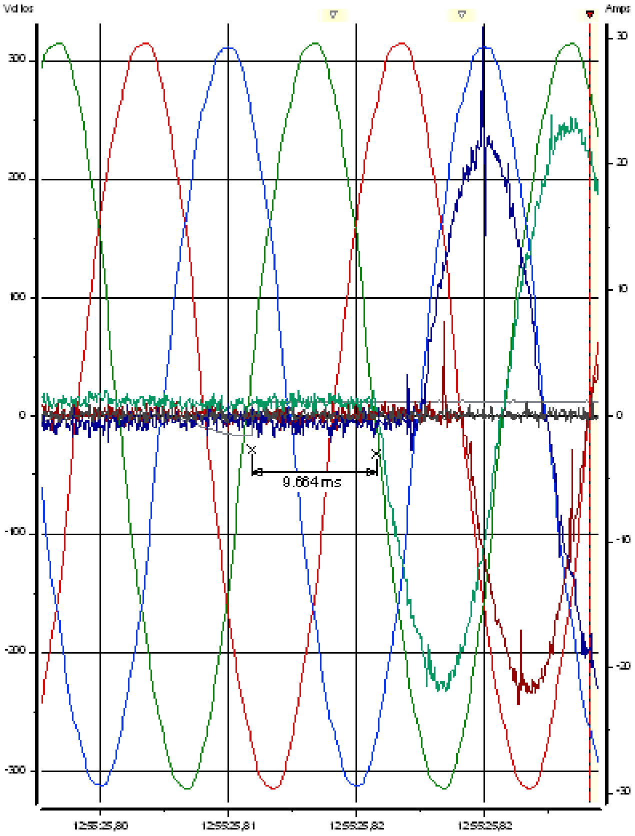

Figure 3-20: V and I measurements: Delay at connection # Resistive load (Round 01)

At another round (see Figure 3-21) the measured delay for the phase A is 8.456ms.

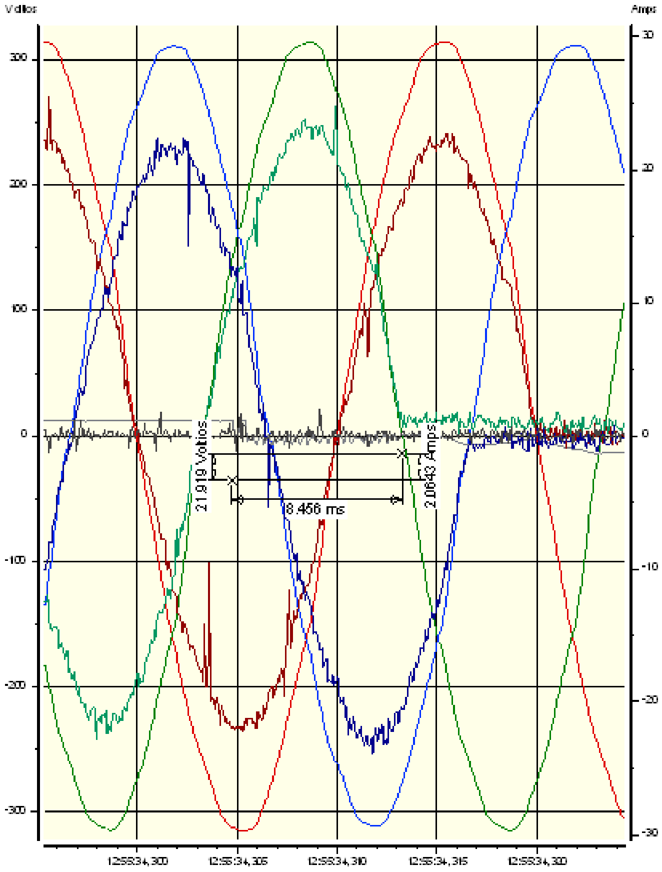

Figure 3-21: V and I measurements: Delay at connection # Resistive load (Round 02)

As shown at Figure 3-22, removing the voltages at the public grid side of the breaker and drawing the trip command signal, the tested condition is clearer. In this case, the delay amounts for 19.949ms.

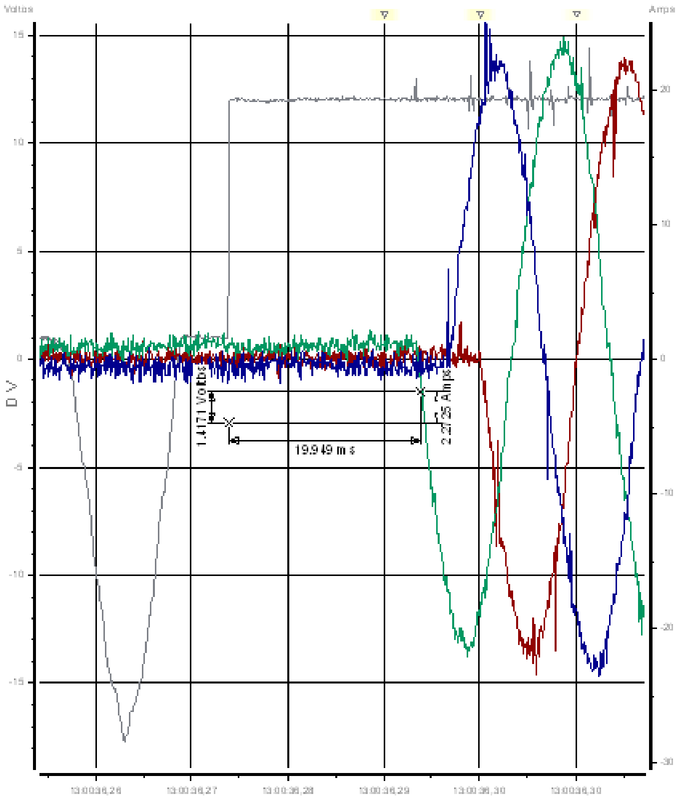

Figure 3-22: V and I measurements: Delay at connection # Resistive load (Round 03)

The obtained measurements are summarized in a tabular format.

		Delay [ms]	
Round	**Operation**	**Phase A**	**Phase C**
01	Connection	9.664	16.313
	Disconnection	8.456	15.105
02	Connection	19.949	26.598
	Disconnection	3.131	9.780
03	Connection	10.498	17.147
	Disconnection	10.762	17.411

3.2.2. Inductive load

A similar test is conducted with a different load type because the basic functionality testing has demonstrated that the load characteristics do affect to the switching operation.

At Figure 3-23 the found delay during the first round is measured to 19.034ms for phase A and 25.683ms for phase C. The evolution of the transient in the currents has been reported before.

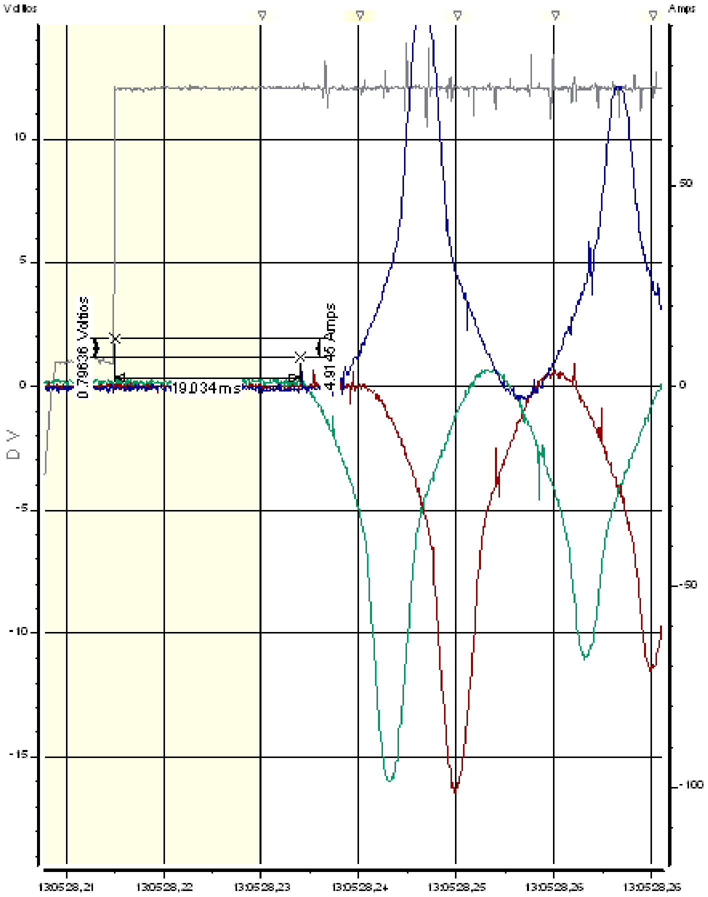

Figure 3-23: V and I measurements: Delay at connection # Inductive load (Round 01)

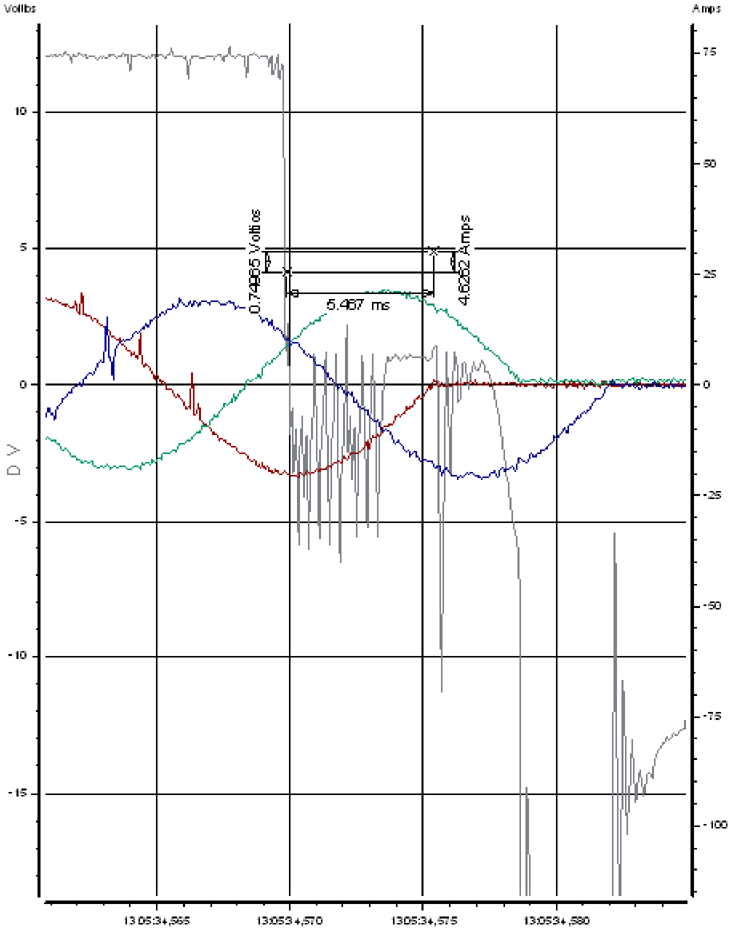

Figure 3-24: V and I measurements: Delay at connection # Inductive load (Round 02)

The measured values are detailed at the following table:

		Delay [ms]	
Round	**Operation**	**Phase A**	**Phase C**
01	Connection	19.034	25.683
	Disconnection	5.467	12.116
02	Connection	9.543	16.192
	Disconnection	17.794	24.443
03	Connection	4.826	11.475
	Disconnection	9.571	16.220

3.2.3. Conclusions

The conclusion is that, after the control signal is sent, the static breaker takes, at most, about one cycle to fulfil the operation with the three phases, either opening or closing, and irrespectively of the type of current being managed.

4. Testing – Transitions: Grid connected from & to Islanded

4.1. Different frequency

The test is intended to analyze the possibilities of connect back the µGrid to the public grid after the system has remained islanded. The eventuality of conducting the process with not frequency control (secondary regulation) available is ensured. The static breaker is operated when the voltage at both sides is close enough[1].

The layout of the laboratory components is depicted at Figure 4-1.

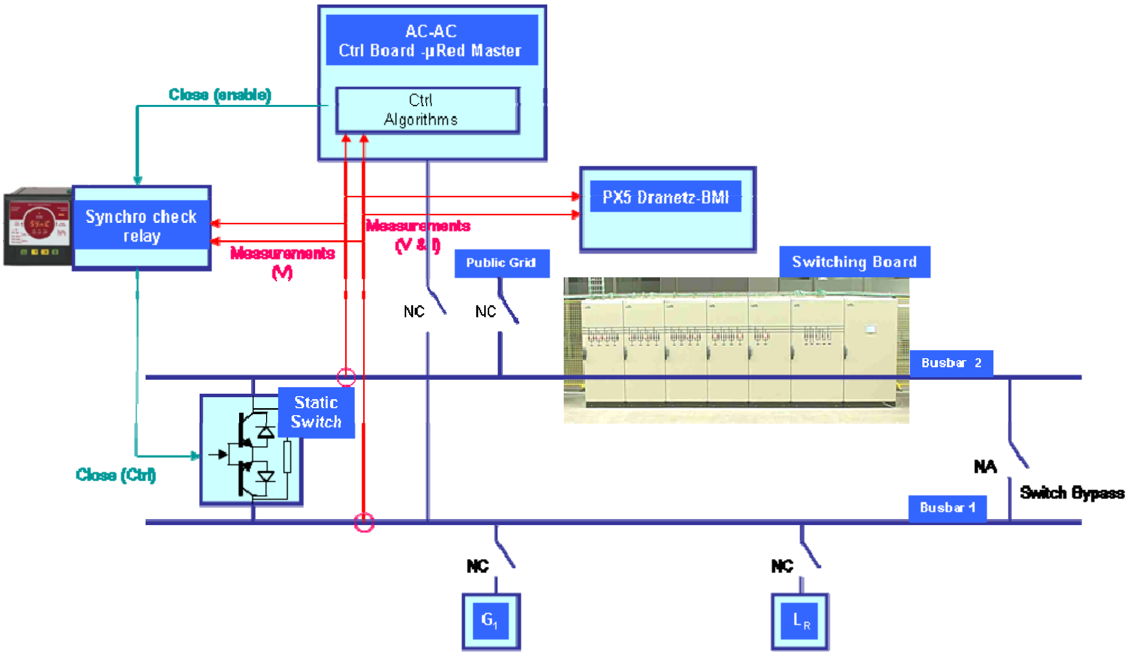

Figure 4-1: Layout and components transitions tests

The initial situation is that the µGrid is connected to the main public grid. The loading of the µGrid is variable in terms of active power load but the reactive power load is kept constant an equal to 5 kVAr.

An AC/AC converter acts as voltage source when the µGrid is islanded and it is programmed with a P-f droop. The offset and slope are such that, for 50 Hz the inverter injects 20kW, at 49.5Hz produces 40 kW and no power at 50.5 Hz;

---

[1] The requirements of the synchro-check relay are always satisfied because the master enabling signal is produced by the relay.

The µGrid is islanded and the AC/AC converter establishes the islanded power system frequency depending on the connected active power demand. Several tests are performed under distinct values of load (5.56kW, 11,11kW, 16,66kW and 22kW).

For each of the different cases (and frequencies) the switch is commanded to close connecting back the µGrid to the public grid. The connection takes place with the enabling signal of the synchro-check relay. The programmed parameters are:

- ∆V = 10% (over 380 Volts)
- ∆f = 1 Hz

The achieved final frequency at islanded mode and the associated resistive load[2] are detailed at the following table:

Round	Load [kW]	Frequency [Hz]
01	0.00	50.50
02	5.56	50.35
03	11.11	50.20
04	16.66	50.06
05	22.20	49.96

Under these conditions, the voltage at both sides of the breaker evolves progressively and converges faster as the difference in frequency is higher. The recording of each test takes two phase to phase voltages at both sides of the breaker (four signals) and the four currents (two at each side).

4.1.1. Case study 01: Island frequency 50.5 Hz

The µGrid is formed by one generator and one load and it is connected to the mains. The inverter injects 20 kW and demand consumes P = 0 kW & Q = 5 kVA. In this situation power is being injected back to the public grid.

Then (see Figure 4-2), the µGrid is isolated from the mains operating the static breaker, the inverter control detects the islanded situation and it comes into voltage source mode (grid forming) and adapts the output power following the power-frequency droop. The droop and

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[2] As stated before, the inductive load is the same for every case: 5 kVAr

its offset had been adjusted so that when the power output is null the voltage frequency is brought up to 50.5Hz on the isolated system.

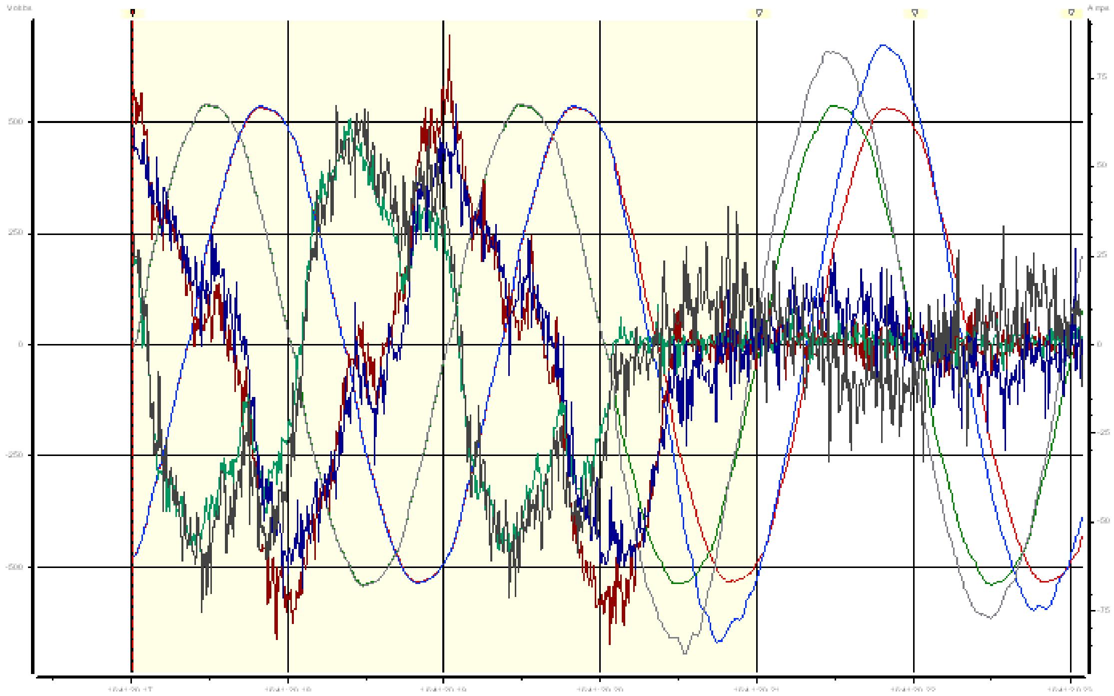

Figure 4-2: V and I measurements: Disconnection from mains # Case 01

As it can be observed at Figure 4-2, once the switch is open, the voltage on both sides of the switch becomes different. On the public grid it remains the same but, on the isolated grid frequency increases (noticeable at sinusoidal voltages zero crossing, the “inside” voltage crosses zero before the “outside” signal) as well as voltage module (inverter V-Q droop).

The Figure 4-3 shows the evolution of considered measurements during the re-connection of the island to the mains. Until the static switch is closed there are two different voltage signals and when it closes there is one single plot.

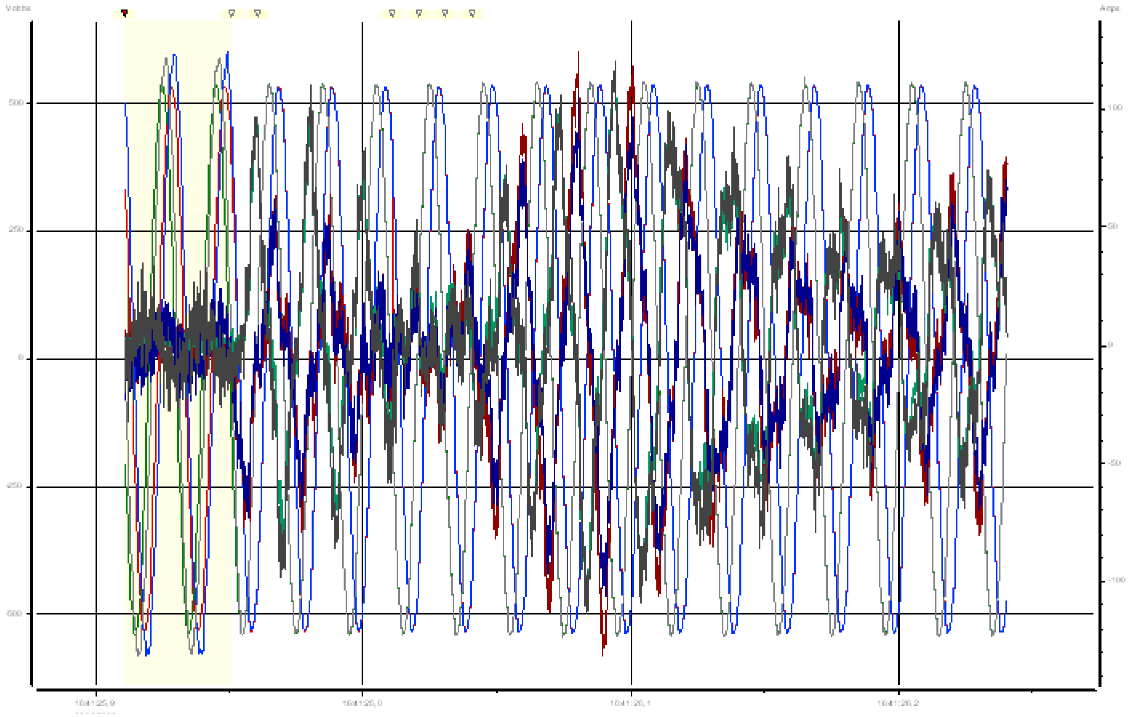

Figure 4-3: V and I measurements: Re-Connection to mains # Case 01

The situation of the currents is similar, until the connection the four signals produce some noise and after it the inverter has to react to the main grid imposing the system frequency moving along its droop curve. For the final 50Hz the generator produces the expected 20 kW.

4.1.2. Case study 02: Island frequency 50.35 Hz

The µGrid is formed by one generator and one load and it is connected to the mains. The inverter injects 20 kW and demand consumes P = 5.56 kW & Q = 5 kVA

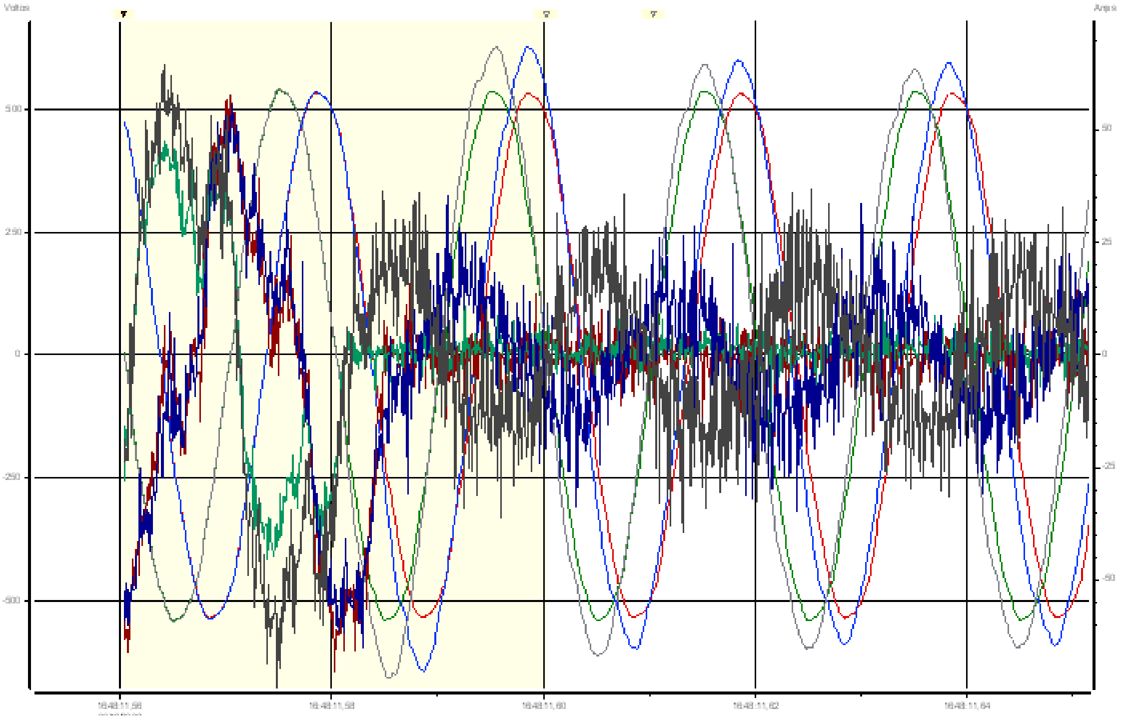

Figure 4-4: V and I measurements: Disconnection from mains # Case 02

After the disconnection (Figure 4-4), the island establishes on 50.35Hz.

In a similar way (Figure 4-5) shows the re-connection back, from islanded mode into grid connected mode. The voltage is stable almost immediately but it takes a few cycles to the generator control to recover (measured through the currents).

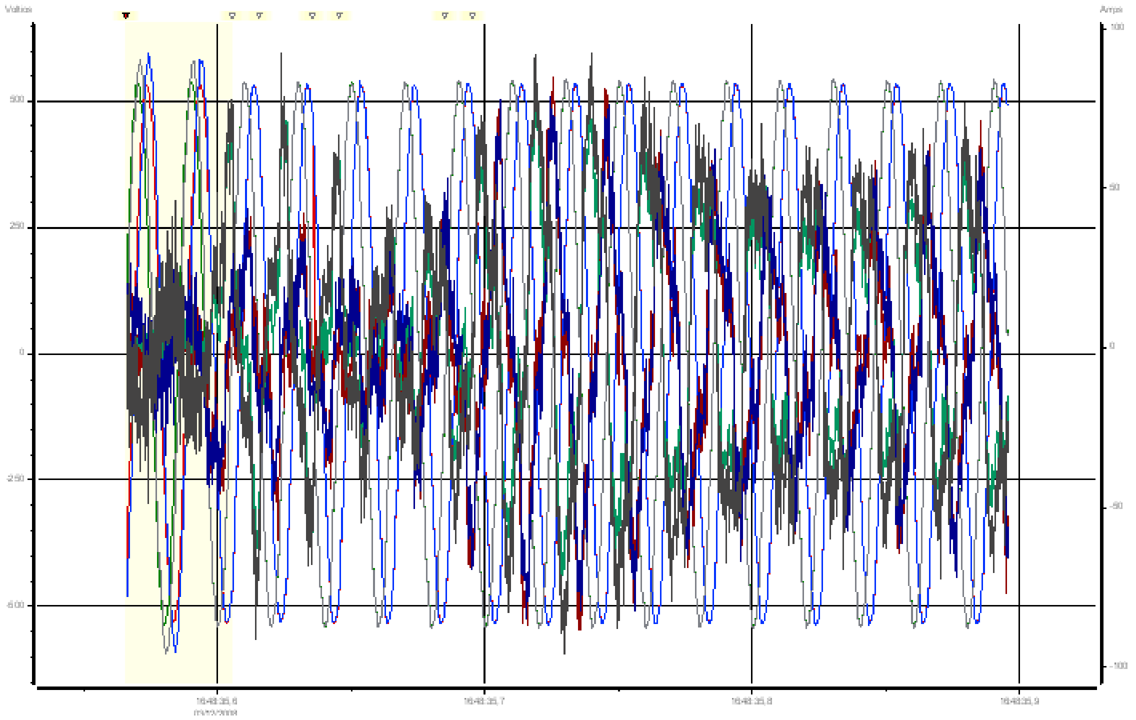

Figure 4-5: V and I measurements: Re-Connection to mains # Case 02

4.1.3. Case study 03: Island frequency 50.20 Hz

The µGrid is formed by one generator and one load and it is connected to the mains. The inverter injects 20 kW and demand consumes P = 11.11 kW& Q = 5 kVA.

In Figure 4-6 and Figure 4-7 the disconnection and reconnection P&Q monitoring data is drawn.

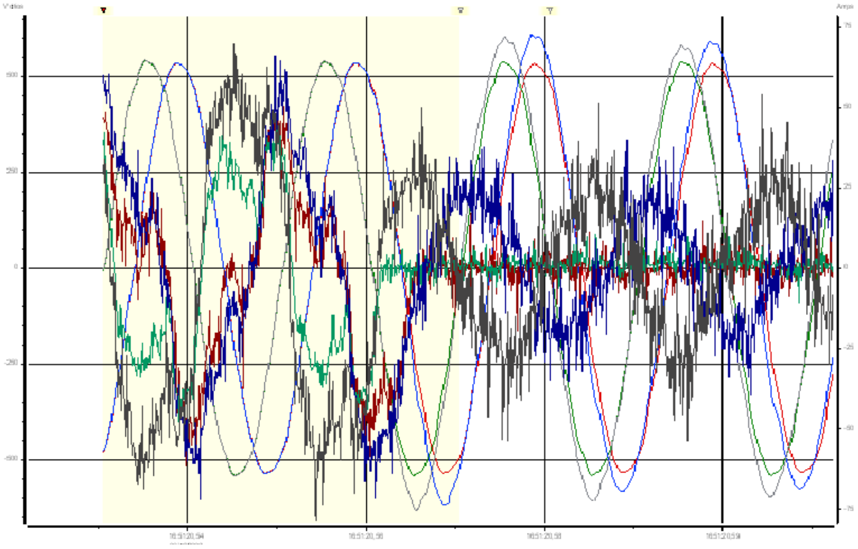

Figure 4-6: V and I measurements: Disconnection from mains # Case 03

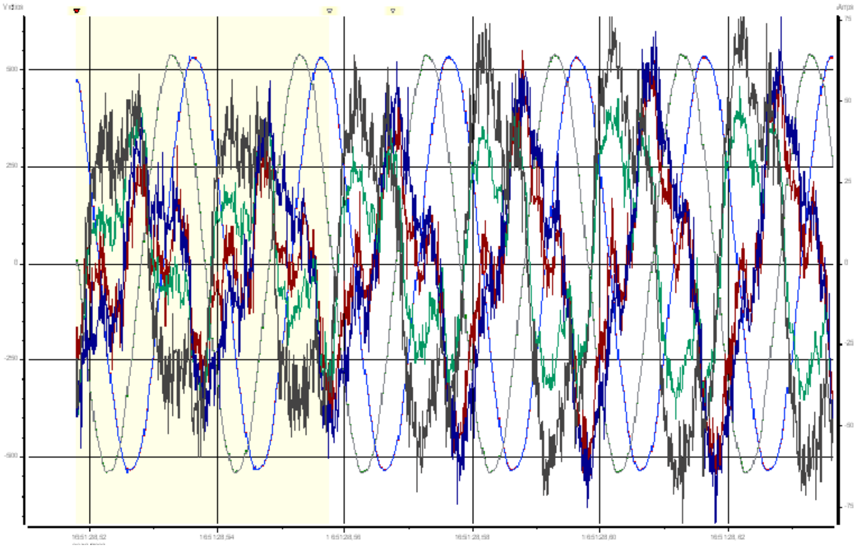

Figure 4-7: V and I measurements: Re-Connection to mains # Case 03

4.1.4. Case study 04: Island frequency 50.06 Hz

The µGrid is formed by one generator and one load and it is connected to the mains. The inverter injects 20 kW and demand consumes P = 16.66 kW & Q = 5 kVA.

At Figure 4-8 and Figure 4-9 the disconnection & reconnection process is shown.

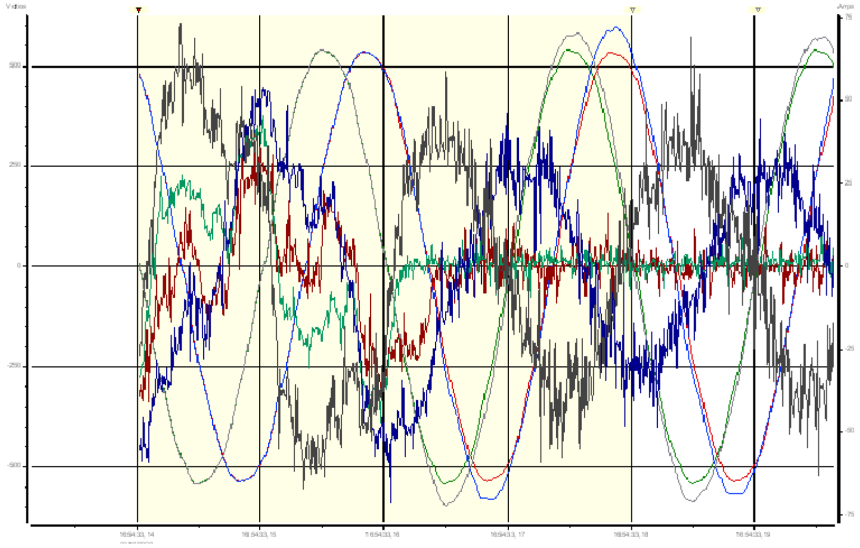

Figure 4-8: V and I measurements: Disconnection from mains # Case 04

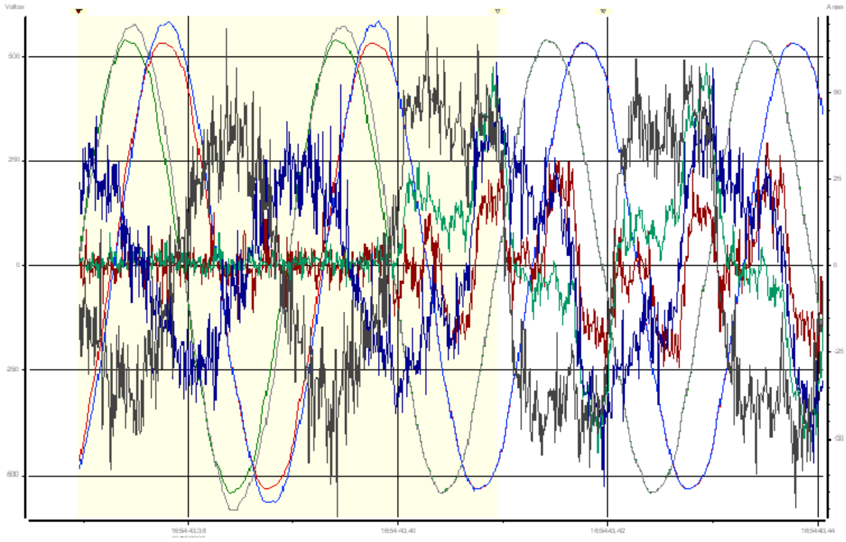

Figure 4-9: V and I measurements: Re-Connection to mains # Case 04

4.1.5. Case study 05: Island frequency 49.96 Hz

The µGrid is formed by one generator and one load and it is connected to the mains. The inverter injects 20 kW and demand consumes P = 22.20 kW & Q = 5 kVA.

The Figure 4-10 and Figure 4-11 report respectively on disconnection & reconnection during case 05.

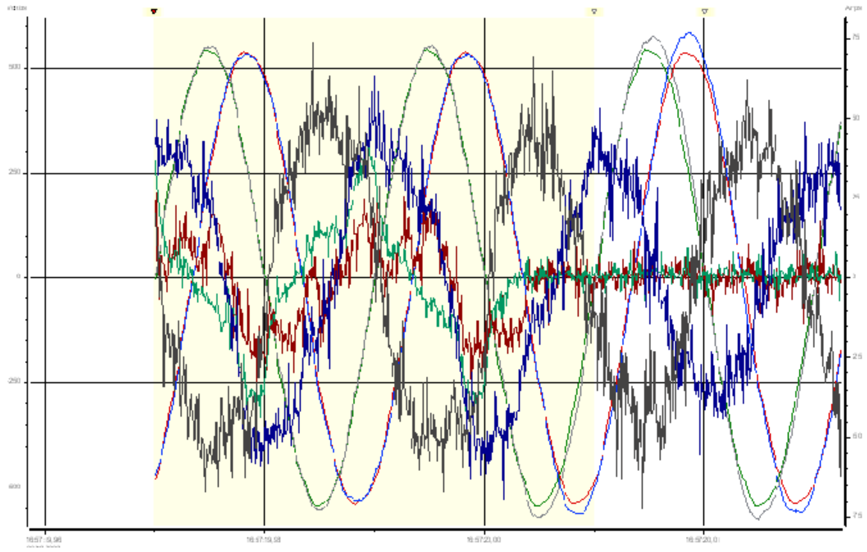

Figure 4-10: V and I measurements: Disconnection from mains # Case 05

It is interesting to note that, as the frequency drift is reduced it takes significantly longer until the synchronization conditions are reached. In case 05 up to 1 minute delay from the main activation signal up to the closing instant.

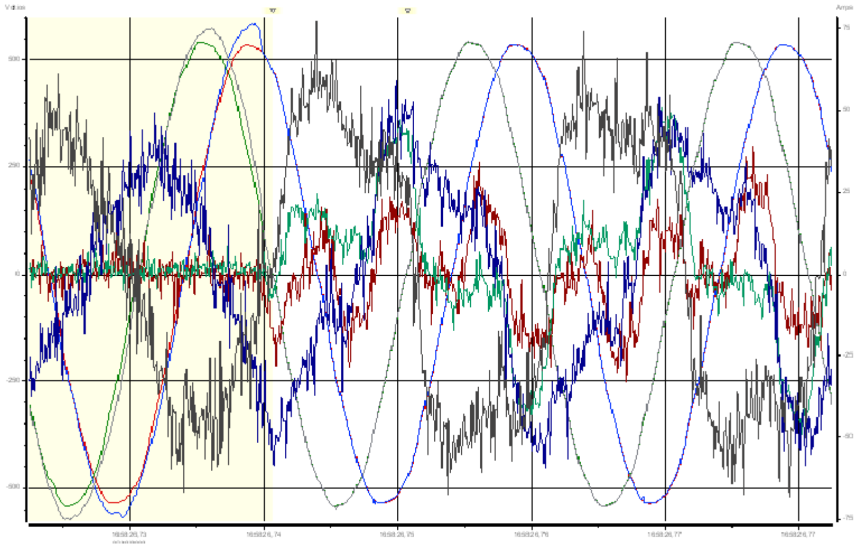

Figure 4-11: V and I measurements: Re-Connection to mains # Case 05

4.2. Same frequency

With the same test equipment layout as for the previous case, the islanded network is commanded back to 50 Hz assuming a supervisory control system is able to manage the µGrid (closing the gap in frequency and ensuring voltages are in phase like any high voltage power plant synchronizer).

In this situation, the voltage is the same (in terms of phase and frequency) at both sides of the breaker although not necessarily in magnitude (acceptable ranges could be as high as 20% depending on the case).

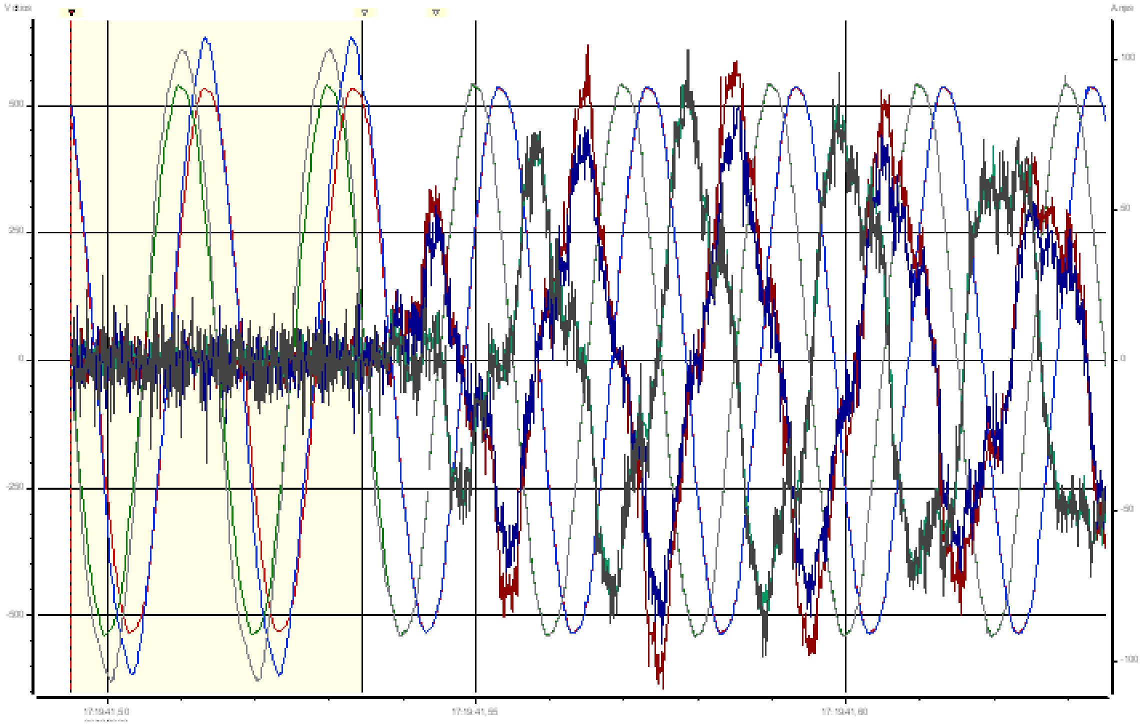

Figure 4-12: V and I measurements: Re-Connection to mains # Case 06 (I)

The Figure 4-12 shows the re-connection of the island to the main grid when both power systems are operating at 50Hz. The transition runs smoothly and currents get stable again after a few cycles when the generator inverter finds itself connected and restores to its initial schedule (20 kW) on current source mode.

The Figure 4-13 shows a similar process with different scales.

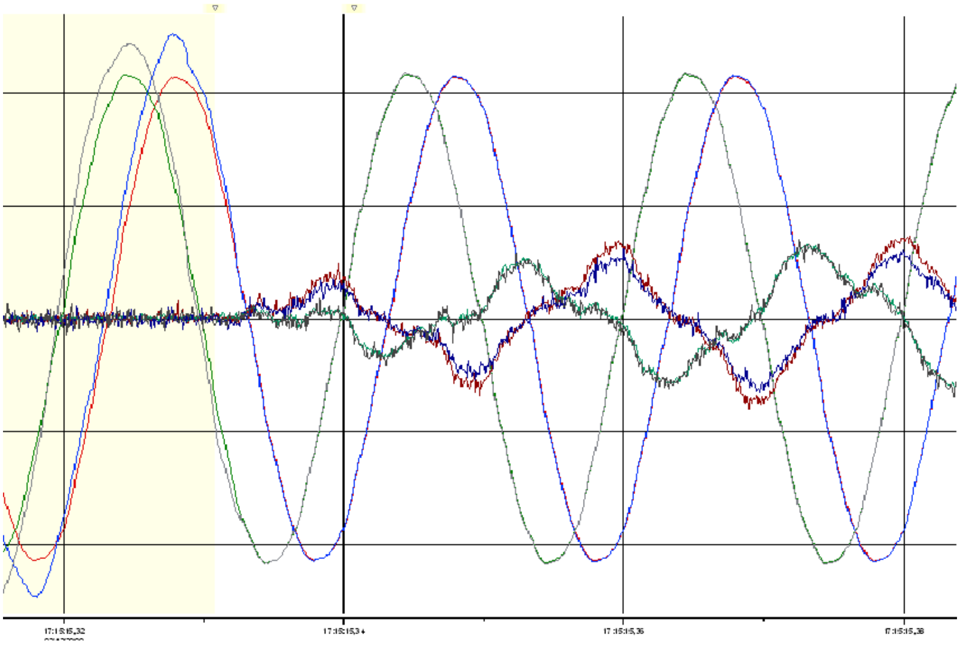

Figure 4-13: V and I measurements: Re-Connection to mains # Case 06 (II)

Advanced Architectures and Control Concepts for More Microgrids

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WORK PACKAGE F

Report on field tests for interconnected mode

Part III – Agent based Energy Management System

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Contents

Index of Figures

Index of Tables

1. Introduction

This document describes the tests done in Labein’s Microgrid facility in order validate and assess the performance of the developed agent based Microgrid Energy Management System.

The description of the control system itself is out of the scope of this document since it is described with great detail in [1] and [2]. The present document focuses on showing the different tests done and their results in order to analyse the behaviour of the microgrid and verify the performance of the developed control and communication system.

The objectives of the performed tests are the following:

1. Validate the usefulness of the secondary control concept applied to microgrids both in grid connected and islanded operating modes.
2. Verify the implementation of the developed control system and asses the usefulness of using innovative multi agent software solutions.
3. Verify the implementation of the communications based on the IEC 61850 standard.

The tests described in the report have been designed in order to make use of the microgrid facility at Labein-Tecnalia. Each of the tests has certain objectives and the complexity of them increases progressively. This way the effect of the different devices participating in the secondary control is studied.

2. Agent based microgrid EMS

During the More Microgrids project, an Energy Management System (EMS) for Microgrids has been developed [1]. For the implementation of the EMS Multi Agent System technologies have been used.

The main characteristics of the developed system are:

- Integration of legacy systems: the EMS allows the easy integration of new devices into the control system. These devices may have different DER technologies, communication protocols etc. This is the case of DER devices where there exist a wide range of technologies and vendors, each with some specific capabilities, functions etc.
- Plug & Play capability: new devices can be added to the control system and others removed from it without the need of stopping the control functions or reconfiguring the EMS.
- Extensible: Due to the modularity of the control system, new functions can be developed and added with little effort. In addition, the new functions can make use of the functionality provided by the remaining components in the control system. This feature makes the EMS suitable for upgrade and extension.

All these characteristics make the developed EMS a good platform for developing functions related to the control of sets of DER components and in particular Microgrids.

The basic functions provided by the agent based EMS are the following:

- Remote control of the devices in the Microgrid: DER devices can be remotely monitored in real time and controlled by defining operation set points, changing operation modes, etc.
- Persistent storage of Microgrid measurements: the different electrical parameters such as power, voltage, frequency, etc. within the Microgrid and those from the connected devices are monitored and stored in a database for its later use and for analysis.

- Automatic schedule tracking: the EMS permits defining a certain power schedule or commitment schedule and this programme is sent and executed automatically by the corresponding device.

The basic features can be extended with new and more complex functions in a straightforward way.

2.1. Secondary regulation implementation

During the project, and as example of a high level function, secondary regulation has been deeply detailed and implemented using the microgrid EMS infrastructure.

The objectives of the secondary regulation are:

1. Microgrid in grid connected mode: In this case the secondary regulation will try to maintain a previously defined power exchange schedule with the main grid. The control system monitors the power exchanged between the main grid and the microgrid detecting any deviation from the desired schedule. Then it calculates revised power set points for connected generators and load switching commands taking into account the price of the deviations (with the main grid) to operate the microgrid in the most economical way.
2. Microgrid in islanded mode: When the microgrid is in islanded mode, the role of the secondary regulation control will be to maintain the frequency in the microgrid as close as possible to a reference frequency. The control system detects any deviations in terms of frequency and dispatches new power set points and load switching commands to restore frequency with the minimum possible cost.

The developed control system is based on a market system internal to the microgrid. In this market, the devices submit their bids based on their own local criteria. The control system considers these bids when assigning the new set points to the generators and the controllable loads.

For testing purposes, the implemented strategies for creating the bids are based on operating costs of generators, load shedding when demand reaches a certain threshold of microgrid generation capacity and deviations prices from the scheduled power exchanges with the main grid.

Further information and details regarding the implementation of the secondary regulation function can be found at [1].

During the execution of the tests of secondary control system, the different devices in the microgrid are progressively added. This means that, at the initial tests only the generators are participating in the regulation system, then flexible loads are added, and finally deviation from the power exchange with the mains are included..

3. IEC 61850 based communications

During the project a communications software module, based on IEC 61850-7-420 standard, has been developed. The communications software implements the data model as well as those services needed to access device data and to operate them.

The IEC 61850 based communications software acts as gateway between the control system described in chapter 2 and the specific proprietary communication protocols used by each of the devices in the microgrid.

The objective of this software layer is to decouple the control system from low level aspects of the used technology and vendor implementations. This enables the easy integration of different devices into the microgrid by just developing the specific communication component adapter to gateway software.

Further and much detailed information about the implementation of the gateway can be found at [2].

4. Microgrid test bed

The microgrid where the tests are performed comprises the DER devices shown in Table 4-1, with total available generation capacity being 100 kW and total consumption being 190 kW. A schematic representation of the microgrid is provided in Figure 4-1.

Table 4-1: DER devices in the microgrid

Device	Description
John Deere 4039 diesel generator	• Active power rating = 50kW • Connected to the microgrid by means of AC/AC converter • Allows both voltage source and current source operating modes
John Deere 4039 diesel generator	• Active power rating = 50kW • Connected to the microgrid by means of AC/AC converter • Allows both voltage source and current source operating modes
Magnetek EG-50[1]	• Active power rating = 50kW • Direct AC or DC connection • Allows both voltage source and current source operating modes
PV	• Three phase • 3.6 kW installed power • Multi crystalline structure modules • Connected through three single phase Sunny Boy 1100 inverters
Avtron Millennium load bank	• Resistive load bank • Three phase delta connection • Independent load steps available are: 5, 10, 10, 25, 50 and 50 kW
Avtron k595 load bank	• Resistive load bank • Star configuration and available neutral wire • Independent load steps available are: 0.5, 1, 1.39, 2.78, 5.56, 11.11 and 16.67 kW
CVM-MINI	• Measuring device monitoring the power exchange with the mains. • Three AC voltage and Three AC current inputs • Communications through RS485 ModBus
CVM-MINI	• Measuring device monitoring PV production. • Three AC voltage and Three AC current inputs • ommunications through RS485 ModBus

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[1] The system integrated also the microturbine system and, in fact, it was used at early testing, communication protocols verified, etc. A failure on the equipment prevented its use for the testing reported in here.

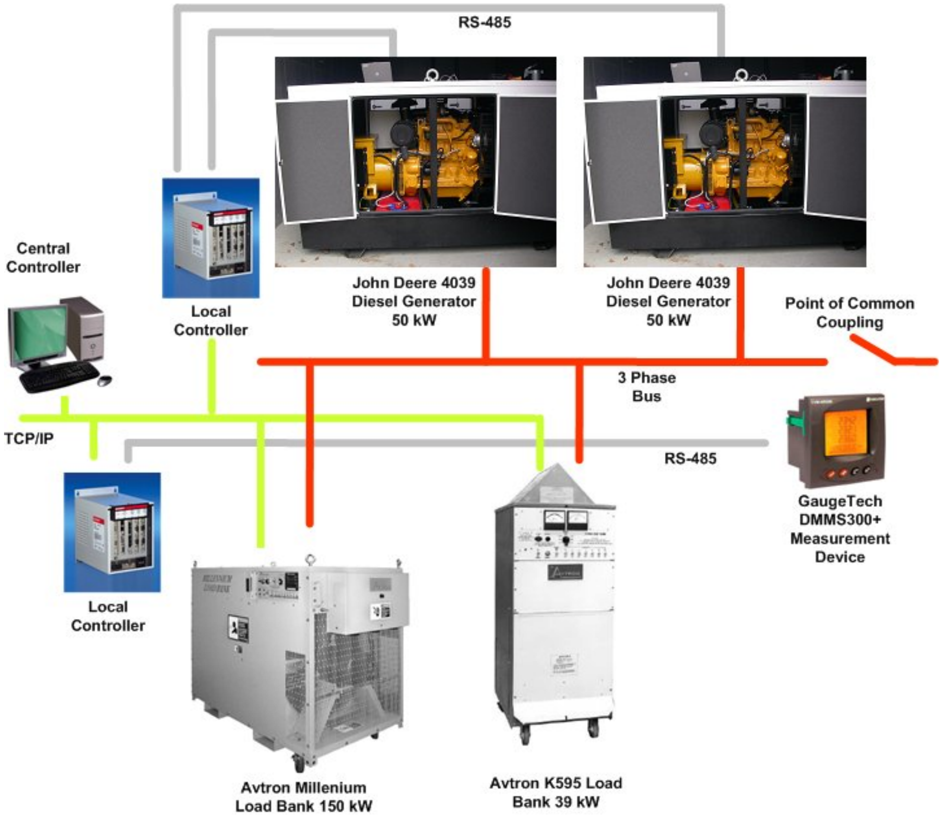

Figure 4-1: MicroGrid schematic diagram[2]

The devices shown in Figure 4-1 are connected to a three phase bus, which in turn is connected to the distribution grid by means of a static switch. At the PCC (Point of Common Coupling) a measuring device is installed to monitor the power exchange with the main grid.

Generating units, load banks and the measuring device at the PCC are connected to the control. The communications are based on the implemented 61850 gateways, which are in charge of translating each specific communication protocol and physical layer to one single and shared data model and protocol based on the 61850 standard. As consequence, the control system obtains measurements and operates the integrated devices using a common interface. The distinction between the sort of supported messages and functions provided by each of them is achieved defining the proper service under the IEC 61850 model

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[2] PV panels are not shown.

The control system is distributed among three different computer hardware units (one central controller and two local controllers in charge of generation units and loads respectively). The EMS's functions are assigned according to the physical links deployed for communications but any combination of host, module and process would be possible.

During the testing process the incremental approach has been applied, that is, not all the devices are operating at every single test. This solution is selected to underline progressively the effect of each considered resource.

5. Control System Configuration

The control system is highly adaptable and configurable. For each specific microgrid desivgn where the tests are conducted the required configuration is described.

5.1. Data monitoring settings

The dynamic data listed in Table 5-1 are gathered and stored in the database every one second[3]. In addition to these data, controlled device settings such as generator operating modes, generation schedules, frequency vs. power drop control activation status and some other relevant information are also stored keeping track of changes.

Table 5-1: Data monitoring settings

Device	Description
Generators	• Active power • Reactive power • Frequency • Voltage • Started/stopped status
Load Banks	• Active power for each load step in each load bank. This value is not a real measurement but it is calculated with the nominal power and the on/off status • On/off status of each step
Measurement devices	• Active power • Reactive power • Frequency • Voltage

---

[3] Note that this measurement gathering rate is too high for a real microgrid, but since in the tests we want to study the behaviour of the microgrids in detail it is used during the testing process.

5.2. Secondary control bid matching settings

In accordance with the generating unit reaction times, the secondary control algorithm is executed every five seconds. This time defines the maximum duration of any power (when operating in grid connected mode) or frequency (when operating in islanded mode) excursion that may take place after an unbalance between generation and demand.

In addition, when operating in grid connected mode there is a 1 kW threshold for power deviation: this means that power deviations lower than 1 kW are neither considered nor corrected by the control system. In case the microgrid is operating in islanded mode, the 1 kW deadband indicates the tolerance in terms of the power.

5.3. Power schedule at the PCC

For the tests done with the microgrid connected to the main grid, a power schedule of zero is set at the PCC; that is, the control system will try to maintain the power imported and exported from the main grid at zero. Thus the microgrid will generate its own electricity consumption. The planned power exchange schedule at the PCC is defined by entering it in the database and updated when needed.

5.4. Reference Frequency setting

When operating in islanded mode, the reference frequency is set to 50 Hz. This is the frequency that the control system will try to restore after any load or generation change occurs.

5.5. Demand profile in the microgrid

The demand shape to be simulated by the loads in the load banks is based on a typical summer weekday demand profile at Labein-Tecnalia’s headquarters building. Consumption increases gradually from 07:00 peaks at 14:00 and starts decreasing when the working day ends at 18:00. The shape is scaled to fit the available loads banks and the connected generation at each of the performed tests.

Figure 5-1 shows the demand profile of the selected day corresponding to Labein-Tecnalia's building. The demand profile is scaled and entered by the microgrid operator into the system's database, and then it is automatically executed by the load schedule tracking function in the control system.

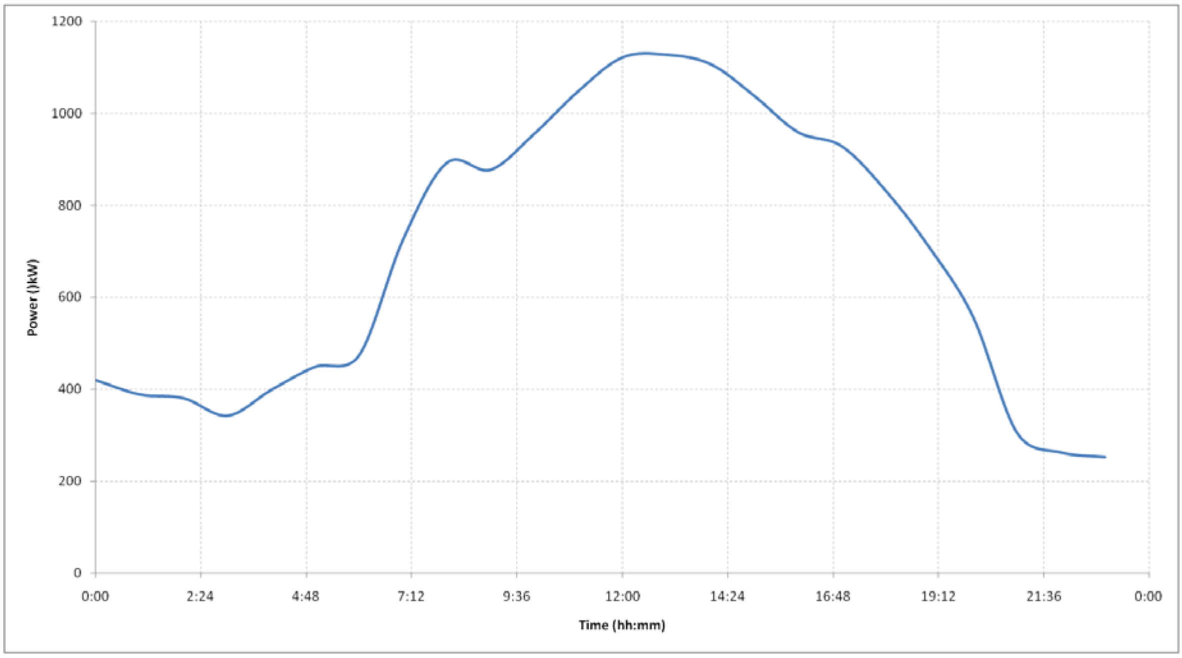


Figure 5-1: Demand profile

Note that for speeding up the execution of the tests, each hour in the real demand profile has been reduced to one minute.

5.6. Bids for participating in the secondary control

The secondary regulation control system enables each device to have its own secondary regulation bid. The bid creation system can be implemented so that it is automatically changed when the device circumstances require or manually modified by the device operator. All these bids are entered into the control system by means of provided graphical user interfaces.

For the tests, each generator, some of the loads and the point of common coupling submit their bids according to the criteria described below.

5.6.1. Bids for generators

The generators that participate in the secondary regulation control are those with dispatchability capabilities: two diesel generators. In contrast, renewable power sources are usually non controllable and therefore are left out of the secondary regulation game.

The bids for the two diesel generators are defined taking into account operating cost data provided in [3] and fuel cost data provided in [4]. The resulting cost rate values are given in Table 5-2. Note that even though the two diesel generators used in the test bed are actually identical, one of them is assigned the cost rates of a microturbine. In this way the behaviour of the system when different generating technologies are used can be tested.

Table 5-2: Cost rate (kW/€)

Generator type	Rated Power (KW)	Full Load (100%)	Reduced Load (75%)	Mid Load (50%)
Diesel	50	0.195576	---	0.226452
Microturbine	50	0.157917	0.135557	0.116876

The data in Table 5-3 are first interpolated to obtain the cost rate curves and then derived to obtain the marginal cost curves (1) & (2).

$$MC_{\mathrm{diesel}} = 0.1647 \qquad (1)$$

$$MC_{\mathrm{microturbine}} = 0.0021 \cdot \mathrm{P} + 0.0427 \qquad (2)$$

Then, the above incremental cost curves are divided in 1 kW power steps, so the final secondary control bids are obtained as shown in Table 5-3.

Table 5-3: Bids for generators (kW/€)

Power (kW)	Diesel Marginal Cost (€/kWh)	μTurbine Marginal Cost (€/kWh)	Power (kW)	Diesel Marginal Cost (€/kWh)	μTurbine Marginal Cost (€/kWh)	Power (kW)	Diesel Marginal Cost (€/kWh)	μTurbine Marginal Cost (€/kWh)
0	0.1647	0.0427	16	0.1647	0.1099	32	0.1647	0.1771
1	0.1647	0.0469	17	0.1647	0.1141	33	0.1647	0.1813
2	0.1647	0.0511	18	0.1647	0.1183	34	0.1647	0.1855

Power (kW)	Diesel Marginal Cost (€/kWh)	μTurbine Marginal Cost (€/kWh)	Power (kW)	Diesel Marginal Cost (€/kWh)	μTurbine Marginal Cost (€/kWh)	Power (kW)	Diesel Marginal Cost (€/kWh)	μTurbine Marginal Cost (€/kWh)
3	0.1647	0.0553	19	0.1647	0.1225	35	0.1647	0.1897
4	0.1647	0.0595	20	0.1647	0.1267	36	0.1647	0.1939
5	0.1647	0.0637	21	0.1647	0.1309	37	0.1647	0.1981
6	0.1647	0.0679	22	0.1647	0.1351	38	0.1647	0.2023
7	0.1647	0.0721	23	0.1647	0.1393	40	0.1647	0.2107
8	0.1647	0.0763	24	0.1647	0.1435	41	0.1647	0.2149
9	0.1647	0.0805	25	0.1647	0.1477	42	0.1647	0.2191
10	0.1647	0.0847	26	0.1647	0.1519	47	0.1647	0.2401
11	0.1647	0.0889	27	0.1647	0.1561	48	0.1647	0.2443
12	0.1647	0.0931	28	0.1647	0.1603	49	0.1647	0.2485
13	0.1647	0.0973	29	0.1647	0.1645	50	0.1647	0.2527
14	0.1647	0.1015	30	0.1647	0.1687			
15	0.1647	0.1057	31	0.1647	0.1729			

5.6.2. Bid for the power exchange at PPC

When the microgrid is working in grid connected mode, if the generation costs are high enough it may be worth to pay the price for deviations in exchanged power with the main grid.

In the test cases, the price for deviations for importing power from the main grid it is set at 0.2154 €/kWh. The control system is very sensitive to this parameter since above this price all power is imported from the main grid and below all power is produced inside the microgrid.

5.6.3. Bids for shedding loads

Finally, the bids for the three loads which participate in secondary control are set in such a way that they are shed gradually when 80% of the total generation capacity is reached. Table 5-4 shows the prices for load shedding:

Table 5-4: Bids for non critical loads

Load	Rated Power (KW)	€/kWh
k595-5	5.56	0.18
k595-6	11.11	0.19
k595-7	16.67	0.20

All these bids are entered into the control system by means of the graphical user interfaces provided by the respective bidder agents in the EMS.

5.6.4. Graphical representation of the bids

Figure 5-2 shows the graphical representation of the bids. According to them, and if all the devices are participating in the secondary regulation system, the first device to be dispatched should be the microturbine until the first 28 kW the next 50 kW should be provided by the Diesel, then another 10kW should be given by the microturbine and finally the rest of the power should be imported from the main grid (in case operating in grid connected mode

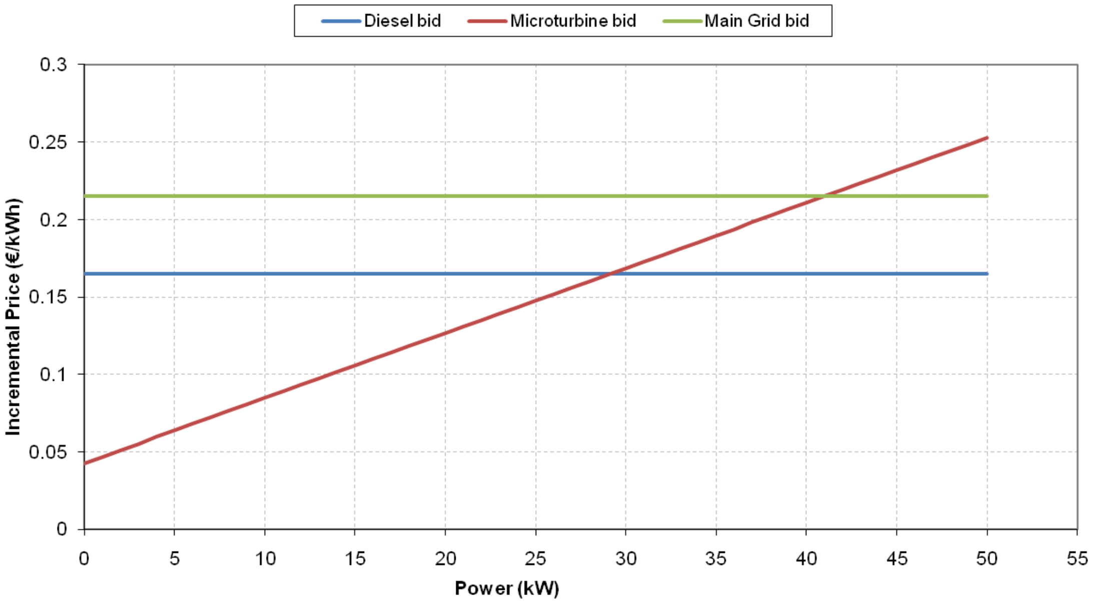


Figure 5-2: Graphical representation of secondary regulation bids

6. Overview of the performed tests

The Table 6-1 indicates some test that are performed and that are described in detail in following sections. These tests have been designed in order to analyse the behaviour of the control system and the microgrid under different conditions.

Tests have been done both when the microgrid is operating in islanded mode and when it operates in grid connected mode.

Table 6-1: Overview of the tests performed

Test Code	Microgrid mode	Diesel 1 mode	Diesel 2 mode	μTurbine mode	PV mode	Load control	Main grid mode
C1	Connected	Current source	Current source	N/A	N/A	No	Not participating
C2	Connected	Current source	Current source	N/A	N/A	Yes	Participating
I1	Islanded	Current source	Voltage source	N/A	N/A	No	N/A
I2	Islanded	Current source	Voltage source	N/A	N/A	Yes	N/A
I3	Islanded	Current source	Voltage source	N/A	Current source	No	N/A

7. Test results in grid-connected mode

This chapter describes the most representative tests done w the microgrid is in grid operating mode.

7.1. Test C1

7.1.1. Description

This is the most basic test performed in grid connected mode. Some design decissions have been taken consideration:

- Secondary control cycle is set to 20 seconds.
- For this test the only devices participating in the secondary regulation control are the two diesel generators.
- The two load banks are scheduled so they follow the consumption pattern in Figure 5-1 scaled to a maximum of 100 kW.
- None of the loads submit any secondary regulation bids.
- Regarding the power exchange with the main grid there is no any bid accounting for deviation prices, therefore the secondary regulation will try to restore the zero power exchange.
- This test has been performed with both diesels submitting the same bids:

Table 7-1: Bids for the diesel generators in C1 test

Power (kW)	Diesel Marginal Cost (€/kWh)
5	0
15	0.1
30	0.2
50	0.3

7.1.2. Objectives

The objective of the test is to verify the correct function of the developed control system in the simplest test bed. We want to verify that the power exchanged with the main grid is maintained close to zero and that the diesel generators' power outputs behave as expected according to their bids.

7.1.3. Results

Figure 7-1 shows the results of the test. The measurement data has been retrieved from the control system's database and plotted in a figure. The shown data is the active power measurements of the two diesel generators, the load bank and the power exchange with the main grid.

From the results the following ideas can be remarked:

- Each time a load change occurs there is a sudden change in the power exchange with the main grid. This is because the two diesel generators are operating in current source mode, so at the very first instant all needed power to cover the reduction or increase of load is supplied by the main grid. This can be seen at times 31:03, 33:01, 34:02, 35:02 and so on.

- When the secondary control realizes that the power exchange with the main grid is greater than the tolerance value, it assigns the corresponding set points to the diesel generators in order to feed the microgrid load. The maximum deviation time is 20 seconds: the same as the duration of the secondary regulation algorithm cycle. In this test the maximum deviation time is produced between 41:50 and 42:04, which is 14 seconds approximately.

- For this case the bids submitted by the generators are both the same and the power dispatched to them depends on how the algorithm orders the bids. The figure shows how the power is shared among the two diesel generators, the Diesel 2 generator is assigned first and the Diesel 1 generator acts as the base power. When the Diesel 2 reaches its maximum 50 kW power the diesel 1 is in charge of adjusting the power balance.

- Demand peaks found at 37:00, 42:00 and 48:00 are no real consumption peaks: what happens is that the load is measured taking into account real data about each step's ON/OFF status and the rated power for each step: due to the slight difference between the switching of the loads steps in the load banks, sometimes instant measurement errors occur.

7.1.4. Conclusions

It can be concluded that the test was successfully executed, the power exchange with the grid is maintained to zero while the generators are dispatched according to their bids as expected.

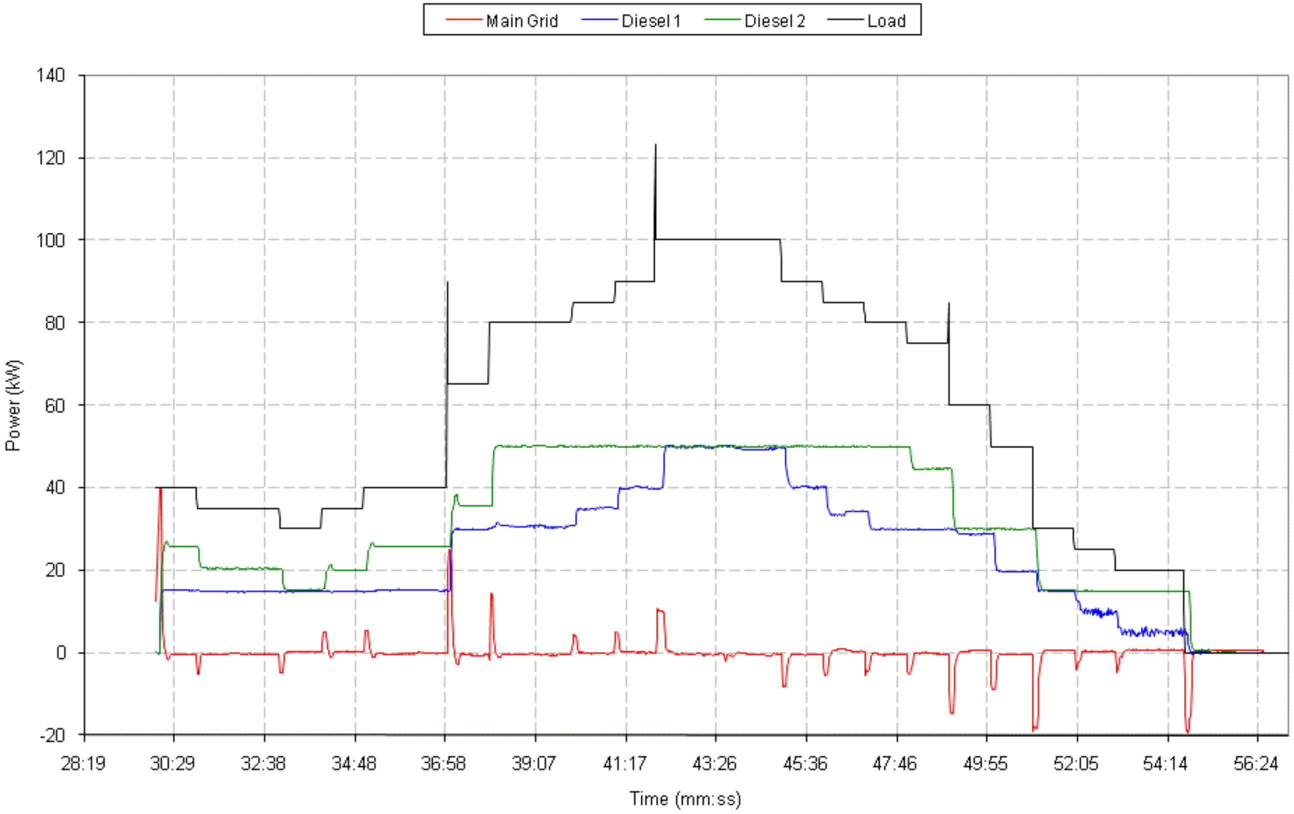


Figure 7-1: C1 Test power plot

7.2. Test C2

7.2.1. Description

This test adds to the Test C2 the load shedding capability and it also takes into account the deviations prices with the main grid.

The following assumptions should be considered:

- For this test the devices participating in the secondary regulation control are the two Diesel generators, three loads in the Avtron K595 load bank and the power imported from the Main grid.
- The two load banks are scheduled so they follow the consumption pattern in Figure 5-1 scaled to 100 kW.
- The diesel generators' bids are the ones shown in Table 5-3 and in Figure 5-2.
- The three loads submit their bids according to Table 5-4. The power of the controlled loads are 5.56, 11.11, 16.67 kW summing a total of 33.34 kW.
- The power deviation price is also taken into account in this test. The price of the power deviation is set to 0.22 €/kWh. It should be noticed that this price is cheaper that the last steps of the most expensive generation unit.

7.2.2. Objectives

The objectives of this test are the following:

- Asses the capacity of the control system to shed load and verify the behaviour of the Microgrid when the power demand is so high that shedding load is used as resource to reduce demand.
- Verify that the control system is able to import power from the grid according to the power deviation price.

7.2.3. Results

The power plot in Figure 7-2 shows the results of the test. The figure shows the following data: electricity consumption as programmed in the load banks, actual measured electricity consumption, power generation of the two diesel generators and power exchange with the main grid.

The following points only describe the points that are different from the previous test:

- At 12:52 the first two controllable loads are switched OFF this occurs when approximately the 75% of the generation capacity is reached. At 12:53 the third load is shed when the consumption reaches the 80% of the generation capacity.
- From 12:55 to 13:01 the price of electricity generation is so high that it is worth to import electricity from the Main Grid. This is way during that time interval the power exchange with the Main Grid is not zero as desired.
- Finally at 4:01 and 5:01 the two controllable loads are switched ON again when the power demand in the microgrid decreases.

7.2.4. Conclusions

The test was successfully executed; the control system is able to shed loads according to the price of electricity in the microgrid. In addition the test results demonstrate that the possibility of importing electricity from the main grid if the power consumption in the microgrid is so high that it is worth to pay the deviation penalties.

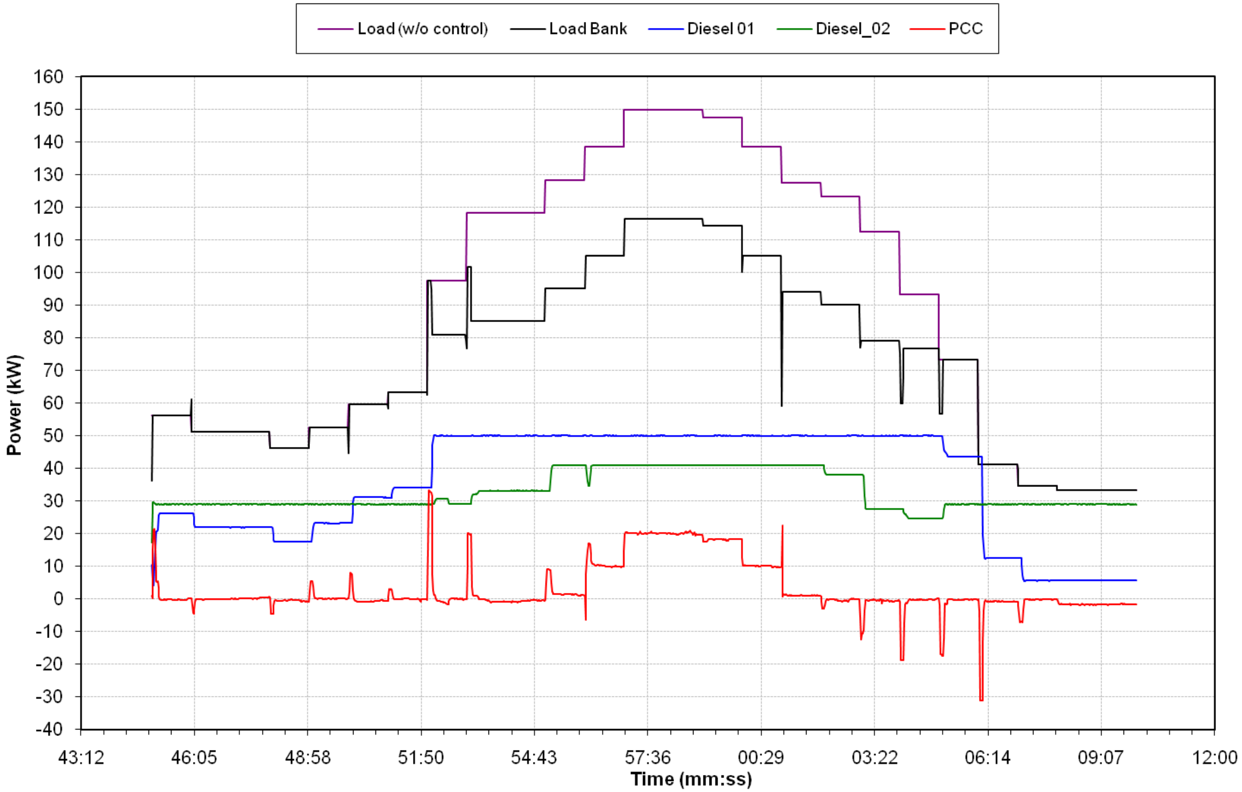


Figure 7-2: C2 Test power plot

8. Test results in islanded mode

This chapter describes the most representative tests performed at Labein-Tecnalia's microgrid when the microgrid is working in islanded operating mode. The tests objective is to verify the implementation of the developed control system and the secondary control concept in islanded microgrids.

8.1. Test I1

8.1.1. Description

This test is done with the microgrid islanded from the main grid. The key points to be considered are:

- The Diesel 1 generator is the only generator participating in the secondary control by submitting the corresponding bid as in Table 5-3.
- The Diesel 2 generator is operating in voltage source mode, that is, it is in charge to fix the frequency and voltage in the microgrid according to the power vs frequency and voltage vs reactive power droops.
- A limit of 30 kW has been set in the power output of the Diesel 1 generator, this way the behaviour when there is enough generation power in the microgrid and when there is not can be compared.
- The Microgrid reference frequency is set to 50 Hz. This is the frequency that the control system will try to maintain during the test.

8.1.2. Objectives

This is the simplest test done with the microgrid in islanded mode. The objective is to verify that the control system works properly by effectively restoring the microgrid frequency to 50 Hz. In order to see the difference between the secondary control able to recover frequency and when there is no enough generation to do it, a limit of 30 kW has been set in one of the diesel generators.

Following tests will add complexity progressively, this way the behaviour of the control system can be easily evaluated step by step.

8.1.3. Results

The active power plot in Figure 8-1 and frequency plot in Figure 8-2 show the active power and frequency of the different devices in the microgrid.

Regarding the frequency plots, some points can be remarked:

- Between 20:12 and 28:00 and between 39:03 and 49:02 the control system is able to recover the frequency to the reference value when there is a change in load that introduces a change in frequency according to the power vs frequency droop of the primary control in the diesel 1 generator (acting as a voltage source).
- Between 28:00 and 39:03 there is no enough power in the microgrid to recover frequency, so a maximum of 0.6 Hz deviation occurs in frequency.
- The frequency taken as reference for the deviation calculation is the one given by the measurement device at the PCC. This measurement device has a resolution of 0.1 HZ, that is the cause of the control system able to regulate only when changes of 0.1 Hz or higher happen.

Regarding the power plot, some ideas are important:

- The Diesel 2 generator is acting as the voltage source, mastering the frequency in the microgrid. As it can be seen when a change in demand occurs the Diesel generator instantaneously adapts its power output matching the load. When the secondary regulation recovers the reference frequency the Diesel 2 generator provides 20 kW which is the power output corresponding to the 50 Hz frequency.

- The power output of the Diesel 1 generator is adjusted by the control system according to the frequency deviations,, since 0.1 Hz is equivalent to 5 kW the power steps of this generator are always multiple of 5.
- Between 28:00 and 39:03 the Diesel 1 generator is at its maximum power and the Diesel 2 is the one in charge of taking all power in excess.

8.1.4. Conclusions

It can be concluded that the results where as expected, the control system is able to restore frequency to the reference frequency. However another frequency measurement could be also taken as reference for the frequency deviation calculation in order to provide more accurate results.

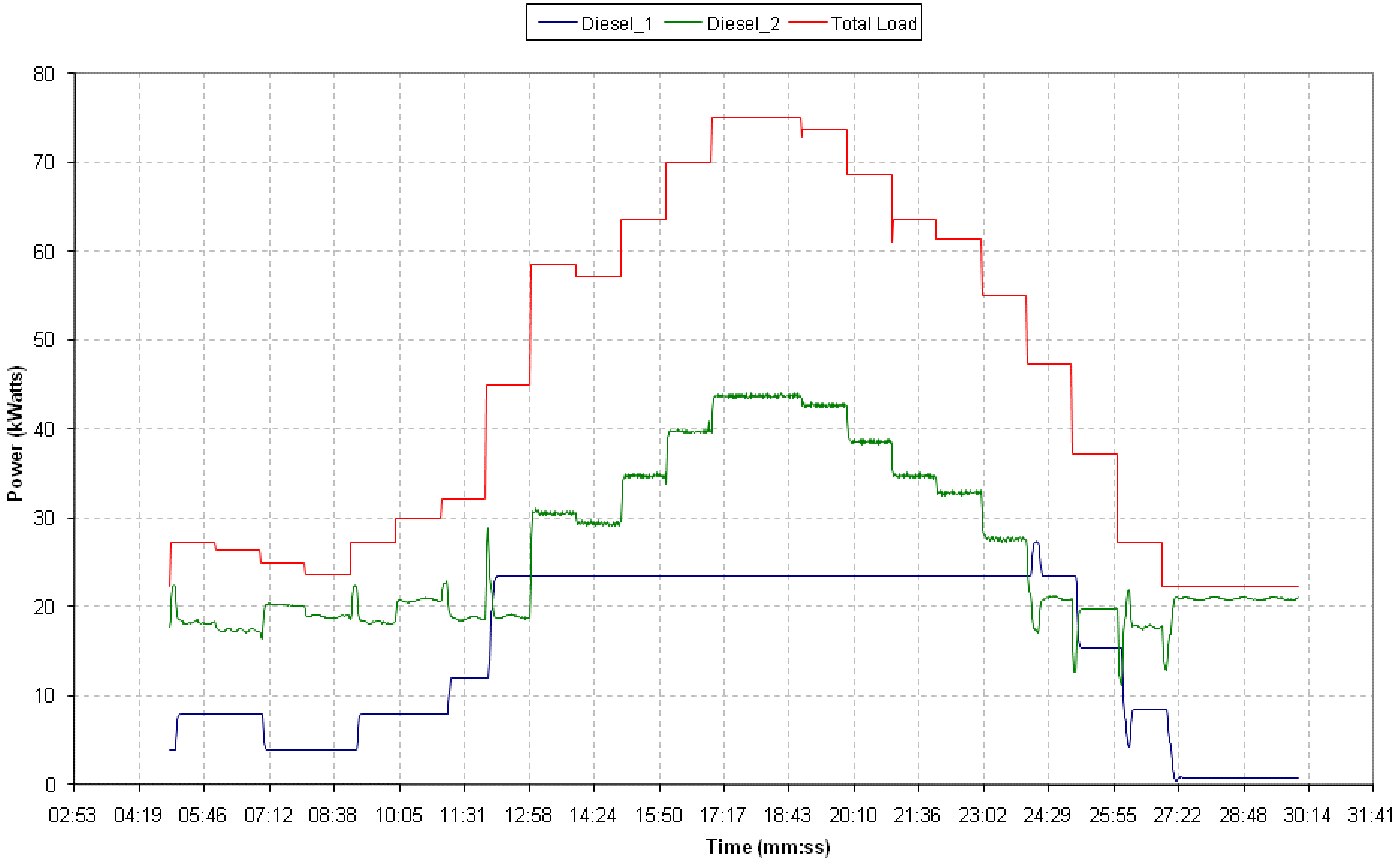


Figure 8-1: I1 Test power plot

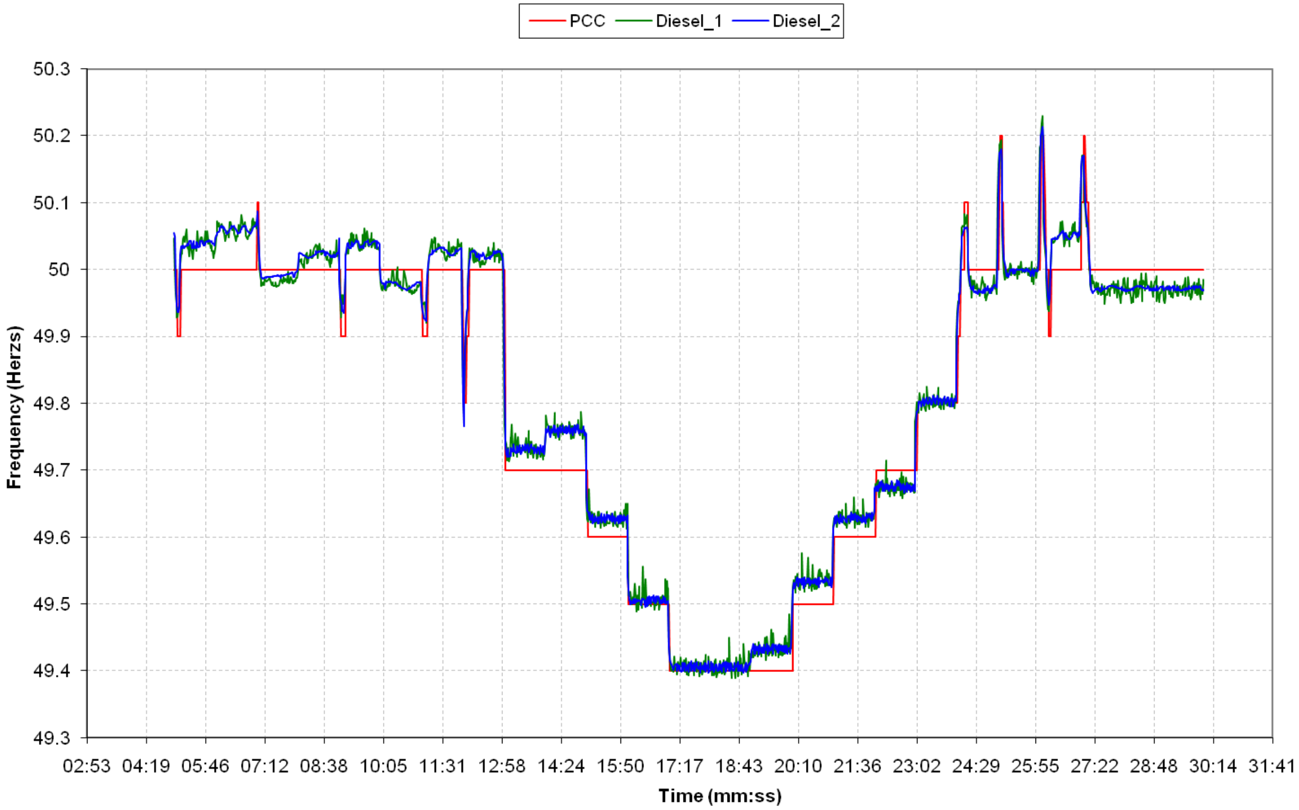


Figure 8-2: I1 Test frequency plot

8.2. Test I2

8.2.1. Description

This test adds to Test I1 the controllability on some of the loads in the load banks and removes the power output limit set in the Diesel 2 generator.

The test is characterized by:

- The Diesel 2 generator is in voltage source operating mode. This implies that it is setting the frequency and voltage in the microgrid according to the frequency vs power and voltage vs reactive power droops implemented in its primary control.
- The Diesel 1 generator is acting as a current source and provides a secondary control bid as in Table 5-3.
- Two loads in the Avtron K595 load bank (k595-5 and k595-7) are also participating in the secondary control system with the bids as specified in Table 5-4.
- The power demand has been programmed in order to follow the shape of the reference Labein-Tecnalia's consumption (see Figure 5-1) scaled to a maximum of 80 kW.
- A reference of 50 Hz in frequency is set. The control system must try to maintain the frequency as closest as possible to that reference frequency.

8.2.2. Objectives

The objective of the test is to analyse the behaviour of the power and frequency in the microgrid when working in islanded mode and with load controllability. The control system should be able to recover the frequency to 50 Hz by assigning generation set points to the Diesel 1 generator and by shedding non critical loads when consumption becomes greater than the 80% of the generation capacity.

Note that in order to maintain the frequency at 50 Hz the base power generation is given by the Diesel 2 generator at 20 kW so the maximum power production in the microgrid is 70 kW.

8.2.3. Results

The active power plot in **¡Error! No se encuentra el origen de la referencia.** and the frequency plot in Figure 8-5 show the results from the test. These figures show the power and frequency measurements retrievd from the control system's database and coming from the two diesel generators, the measurement device at the PCC and the load bank.

The following points are remarked related to the frequency measurements:

- The control system is able to rapidly recover frequency to the reference 50 Hz. The maximum recovery time is 5 seconds which is the period of the secondary control cycle.
- Due to the 0.1 Hz precision of the frequency measurement at the PCC, the control system realizes that there has been a deviation in frequency whenever the deviation is greater than a multiple of 0.1 Hz.

Regarding the power generation and consumption n the microgrid the following poits are discussed:

- The power of the diesel 2 generator fluctuates adapting to the power consumption and provoking the changes in frequency.
- The control system gives to the Diesel 1 generator the set points that allow the frequency to recover to the reference value.
- At 39:46 the two loads in the Avtron k595 load bank are shed, this enables the control system to maintain the reference frequency during all the execution of the test. At 51:00 the first load is reconnected again (k595-7) and at 52:00 the second load (k595-5) is switched don by the control system.

8.2.4. Conclusions

As conclusions it can be said that the control system is able to perform the objective of recovering frequency to the reference value. The control of non critical loads is also a good approach for maintaining frequency at required values, specially when the microgrid is operating in islanded mode and it is more sensitive to load changes.

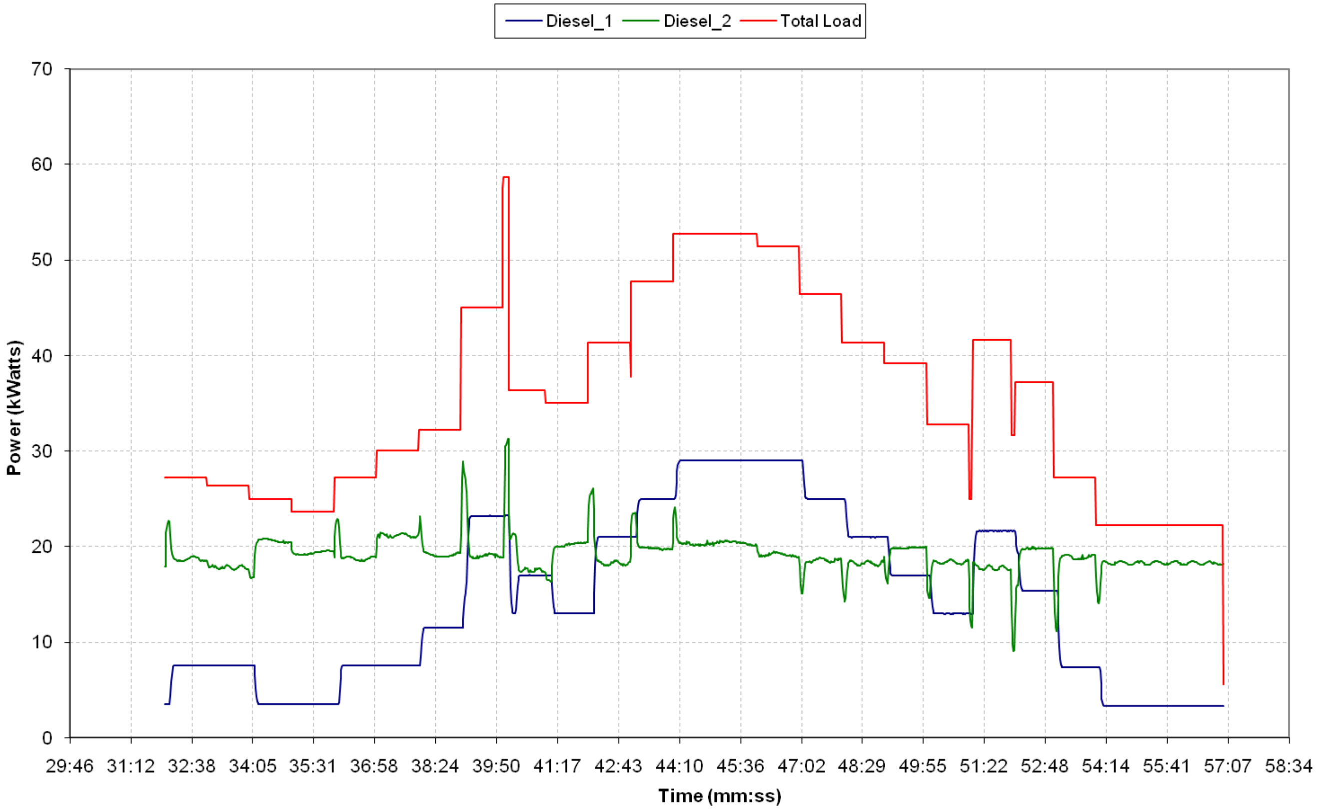


Figure 8-3: I2 Test power plot

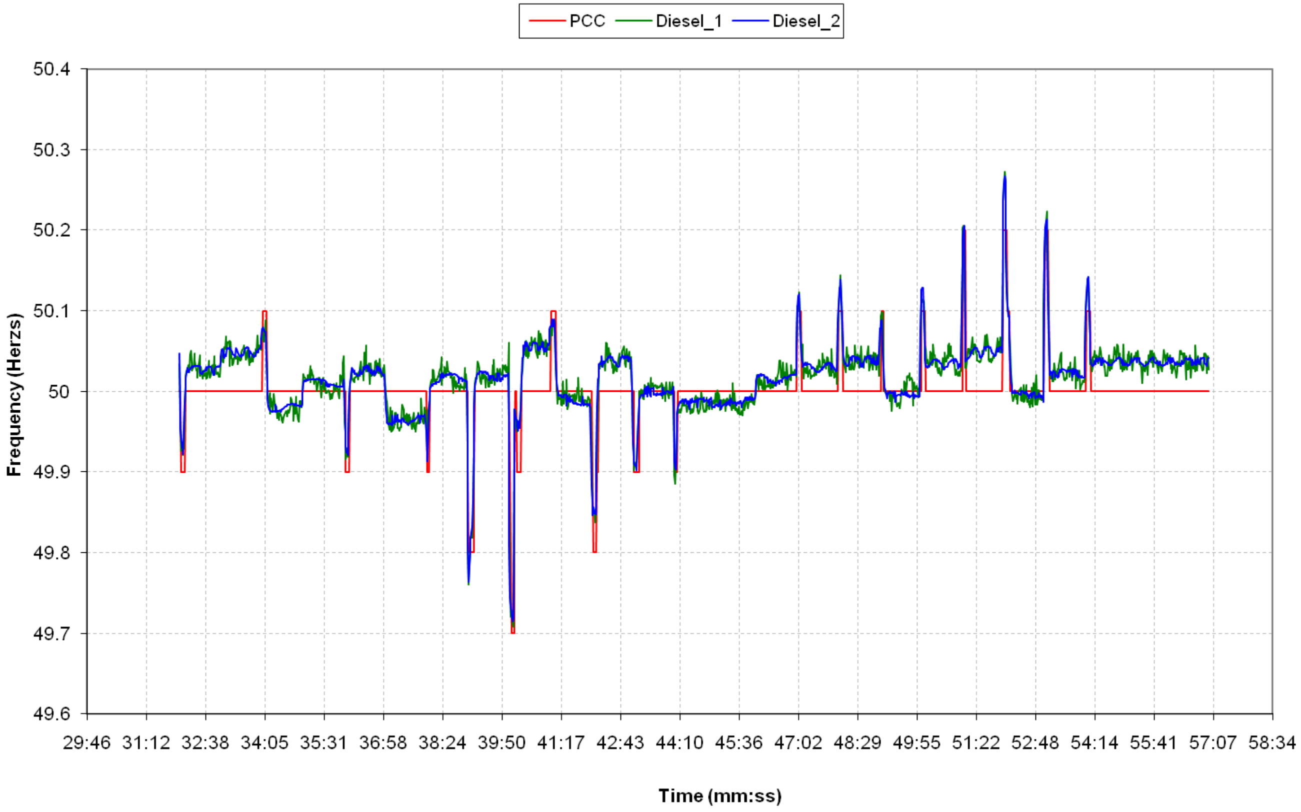


Figure 8-4: I2 Test Frequency power plot

8.3. Test I3

8.3.1. Description

The main point in this test is the addition of a renewable power source injecting power in the microgrid.

The key points are:

- The Diesel 2generator is the acting as voltage source and it is managing the frequency and voltage in the microgrid.
- Diesel 1 generator is in current source operating mode and provides secondary control bids as in Table 5-3.
- In this test, loads are not participating in the secondary control system.
- A PV generator has been connected to the microgrid, the installed power of the PV is 5 kW.
- The reference frequency is set to 50 Hz.

8.3.2. Objectives

The objective of the test is to analyse the behaviour of the microgrid when a renewable source is connected to it. The principal issue about connecting renewables to a microgrid is that they are intermittent sources highly dependant on weather conditions.

8.3.3. Results

Figure 8-6 and Figure 8-7 show the power production and consumption and the frequency in the microgrid respectively.

Regarding the power in the microgrid, some comments are possible:

- At 33:39 the PV generation is connected in the microgrid, from this point on, the PV starts injecting power increasingly until it reaches the maximum (3 kW in a sunny day) at 35:04. It can be noted how at 34:15 the increasing power production of the PV provokes a frequency drift that is corrected by reducing the power output of the Diesel 1 generator.

- As it can be seen from 45:32 to 48:20 the power production of the PV fluctuates quickly, this effect is due to some clouds affecting the power production of the PV. In this period it can be seen how the Diesel 1 generator is dispatched increasing and decreasing its power production in order to adapt the frequency to the reference value.

The frequency in the microgrid shows the following behaviour:

- In general, the PV power production reduces the need of the power from the Diesel 1 generator.
- The quick fluctuations in frequency during the period from 45:32 to 48:20 are caused by the cloudy period affect the PV production. Anyway the PV power is small compared to the consumption and the control system is able to recover quickly the frequency.
- As it can be seen, from 50:52 in advance the frequency is higher than the 50 Hz. This is because the production of the PV originates that, for meeting the load the Diesel 2 generator must produce below the 20 kW base load even if the control system assigns 0 kW production to the Diesel 1 generator. As far as the Diesel 1 units is configured to match 50 HZ when producing 20 kW then there is some sort of excess capacity requiring and offset on the power frequency droop.

8.3.4. Conclusions

It can be concluded that the fluctuations in the PV production are properly handled by the secondary control system that is able to recover quickly the changes in the microgrid frequency.

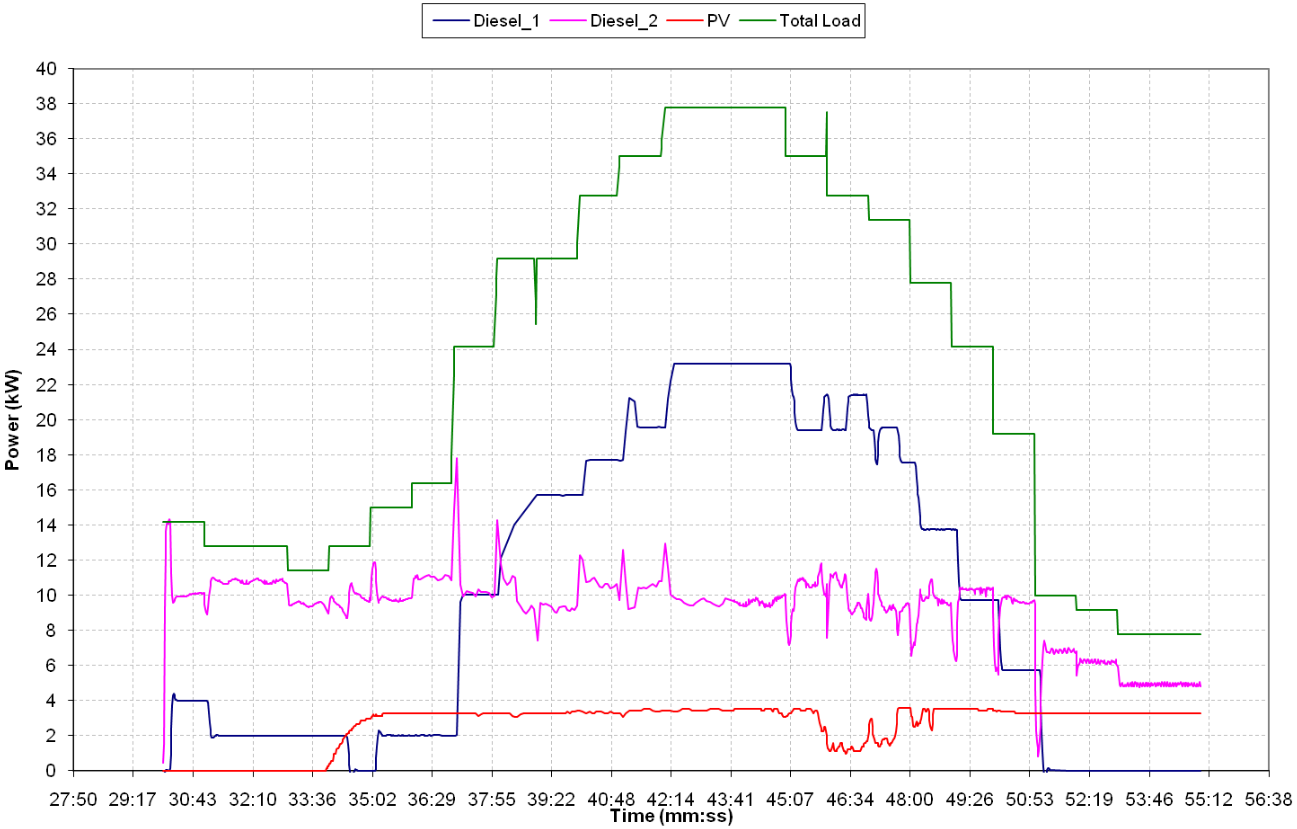


Figure 8-6: I3 Test power plot

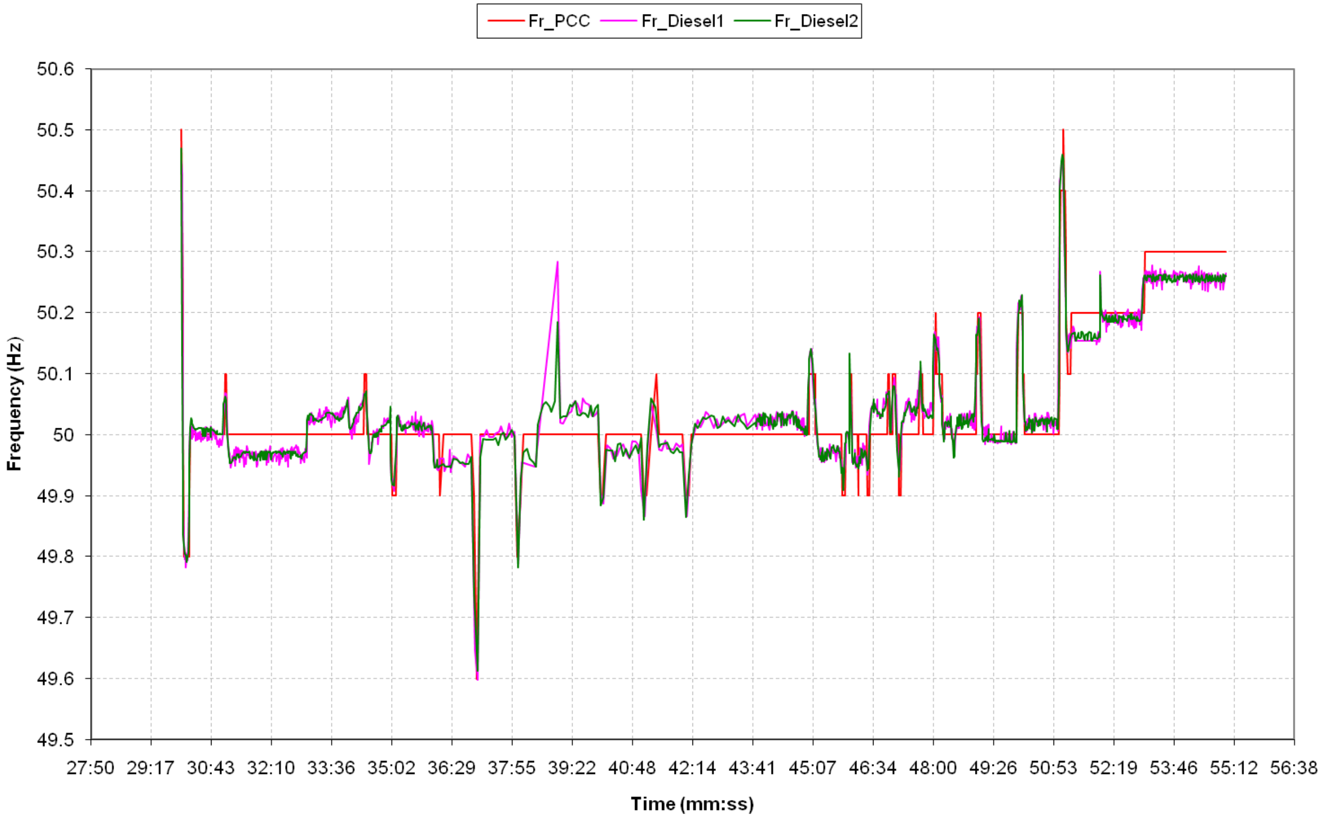


Figure 8-7: I3 Test frequency plot

9. Conclusions

As general conclusions the following ideas can summarize the testing results:

- The control system is able to successfully reduce the power exchange deviations with the main grid when operating in grid connected mode.
- The control system is able to recover the frequency of the microgrid to the reference frequency adapting to the changes in load when the microgrid operates in islanded mode.
- The control system assigns the power set points to generators according to submitted bids. This allows the economical operation of the microgrid both in grid connected and islanded modes.
- The loads are shed successfully and contribute effectively to the objectives of the control system both in grid connected and islanded operation.
- In grid connected mode the penalty prices for deviations are also taken into account and result in the successful determination of the power to be imported from the grid.

In addition to the conclusions listed above and related to the secondary control concept testing in Microgrids, the several key issues can be concluded related to the specific agent based implementation of the system and the use of iEC 61850 based communications:

- The implementation allows an easy integration of devices from different vendors and using different communication protocols and capabilities.
- The plug & play capability of the agent based system allows to install new devices in the system.
- The component based architecture of the agent system allows the easy integration of new functions or upgrading existing functions without affecting the rest of the control system.
- The implementation based in market like structure provides a good way to coordinate the local goals of the devices with the global goals of the microgrid.

Finally, further investigations should be done regarding the connection of greater amounts of renewable energy resources in the microgrids in order to study how larger fluctuations of power production affect the secondary control. Another point for investigation is the connection of storage systems that would provide more flexibility to the microgrid by allowing the intelligent storage of energy when required. The developed control system would allow new research activities in the field since it has been designed to provide flexibility both in terms of new equipment integration and functionality upgrading.

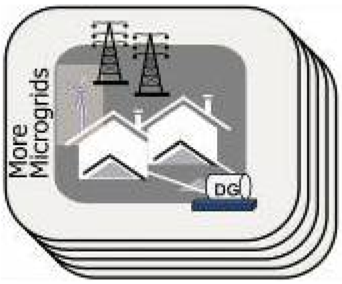
10. References

[1] Jimeno J, Oyarzabal J. DB3: Algorithms for Decentralized Control (MAS). More-Microgrids deliverable for the EC, 2009

[2] Jimeno J, Oyarzabal J. DE4: DG Applied Data Structures and Mapping to Communication Means. More-Microgrids deliverable for the EC, 2008

[3] Gibson GL. Intelligent Software Agents for Control and Scheduling of Distributed Generation. California Energy Commission, PIER Energy-Related Research. Tech. Rep., 2001

[4] Monthly Energy Review January 2009. Energy Information Administration – US Department of Energy, Tech. Rep, 2009.



MoreMicroGrids

Contract No: SES6-019864

WORK PACKAGE F

Report on field tests for islanded mode

Part IV – IEC 61850 based P&C system

Final Version

January 2010

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Contents

Index of figures

1. Introduction

According to the description of work of task TF2, ZIV installed a number of IEDs in LABEIN's microgrid. These IEDs have functions which allow the integration of each generating/storing/load unit for protection purposes, and are based on ZIV's newest line of hardware and software for distribution controllers.

Six micro source controllers (MC) and three micro load controllers (LC) were installed, and also one microgrid central controller (MGCC) was connected to the protection system. Each of these devices is a part of the microgrid's protection system, based on a communications system that relies on an ETHERNET network that is managed by a switch.

In the following Figure 1-1 it's depicted a general overview of LABEIN's microgrid together with the equipments that constitute the microgrid's protection system.

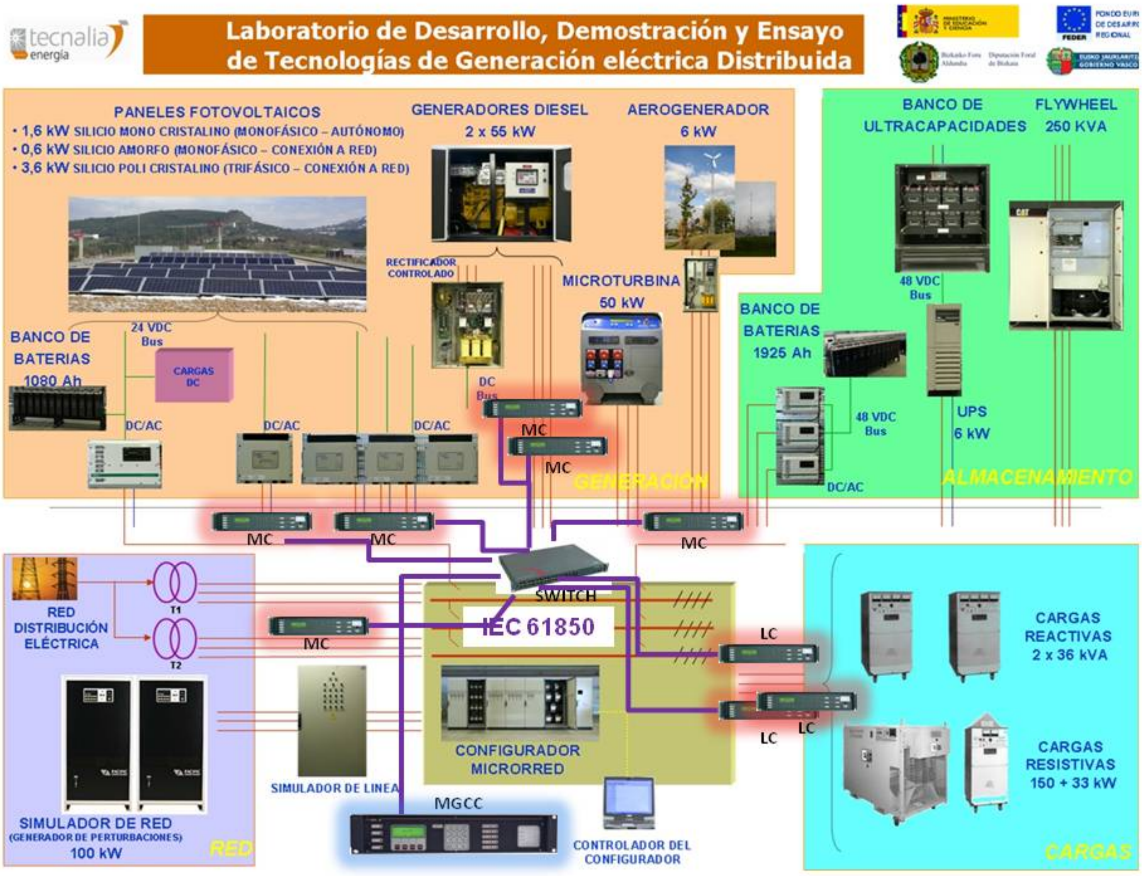


Figure 1-1: LABEIN's microgrid and the protection system

Next list shows the details of the resources that were included in this field test:

Resource	Type of controller	Power
Network Simulator	MC	100kW
Resistive Bank 1	LC	150kW
Resistive Bank 2	LC	35kW
Diesel generator 1	MC	50kW
Diesel generator 2	MC	50kW
Reactive Bank 1	LC	33kVA
Wind mill	MC	6kW
PV panel 1	MC	3,6kW
PV panel 3	MC	1,2kW (phase C)

It needs to be highlighted that all these protection IEDs are exclusively used for monitoring purposes, and not for control or operation purposes. This microgrid is a laboratory demonstrator, and has a configuration system based on contactors that allows configuring it in different ways, with different topologies. But these contactors don't have capacity to break load currents, and less to open short-circuit currents.

MGCC device was installed together with the rest of devices, but finally it doesn't have a specific function within the protection system deployed. In principle, it was intended to be used in centralized communications architectures, but chosen architecture was decentralized. As it will be shown later on, due to the fact that IEC 61850/MMS protocol was going to be used, a decentralized architecture was a sample of the application's advantages of this new international standard.

MC and LC protection devices interface with the generators and loads by means of their analogue and digital inputs. Voltages are measured in a direct way, because IED's voltage analogue inputs have capacity to measure the rated voltage (220Vca) in permanence. Nevertheless, current measurements require the use of sensors because rated currents are over the limits of IED's current analogue inputs; an image of connection of these current sensors can be seen in Figure 1-2.

Figure 1-2: Connection of current sensors

IED’s digital inputs are used solely to obtain information about the status of generators/loads, connected or not connected. This information is provided by the contactors that determine the microgrid’s configuration.

Therefore, having a look on the back of the rack where IEDs are mounted (Figure 1-3), it' can be seen that the only wiring between the devices of this protection system is the ETHERNET links they have with the switch. The rest of wiring is between generators and loads with their respective MC or LC. Despite this much reduced cabling, we'll see that these IEDs are able to perform any kind of shared logic with the highest performance at the fastest speed.

Figure 1-3: Back of rack with IEDs

In the following picture (Figure 1-4), it is possible to see in detail how a MC is wired and the links with RJ45 interface entering the switch.

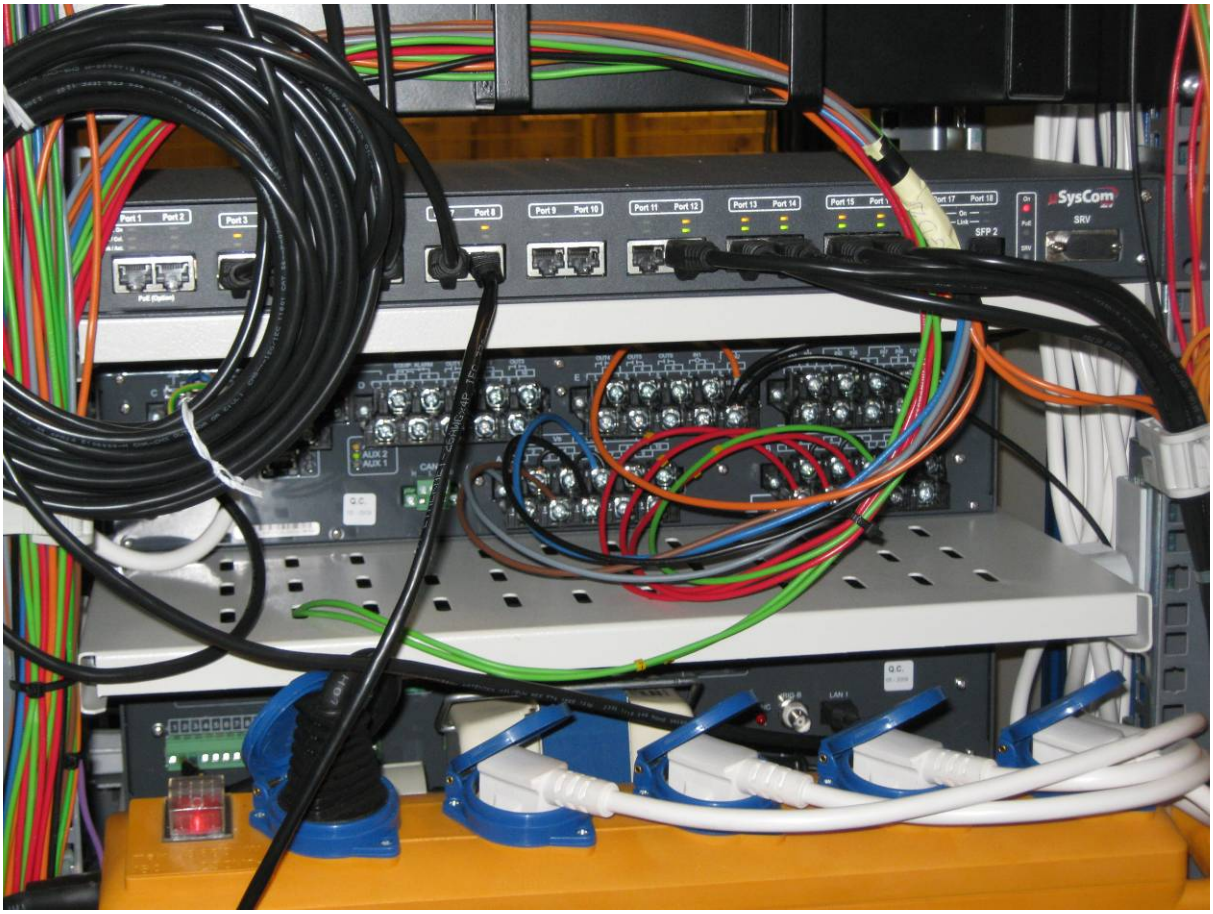


Figure 1-4: Detail of back of the back panel of a MC and the switch

2. Characteristics of Installed Equipments

In this section we are going through the main features and characteristics of IEDs used as MC and LC, as well as the MGCC and the switch.

As it is indicated at the beginning, protection system is formed by nine MC/LC devices, one MGCC device and a switch that is conformance with IEC61850 standard. All these equipments are placed in trays of a rack; some of them can be seen in Figure 2-1.

Figure 2-1: View of the rack with part of the equipments of the protection system

MC and LC functions are solved with the same equipment, one of the newest ZIV's developments, namely IRV.

MGCC function is done by a device call CPT, the latest ZIV's development of an IEC61850 client.

And finally, the switch is also a new development of a sister company, µSysCom, being a rugged communication product that is also compliant with the IEC61850 requirements.

2.1. MC/LC – 8IRV according to ZIV's denomination

Equipment used to realize the functions of MC and LC was a protection relay from a family called IRV. In the following Figure 2-2 and Figure 2-3 two pictures of this multifunction relay can be seen. Model selected is the simplest configuration regarding digital inputs and outputs, and also communications ports, because one of the objectives of this demonstration is to show that microgrid's protection can be done with simple and cheap products.

Figure 2-2: 8IRV model

Figure 2-3: View of one of 8IRV installed in the demonstrator

In the following subsections are described the main features of this relay. In many aspects these characteristics might not to be necessary to fulfil with the requirements of a microgrid's protection, however they were available because they didn't mean an extra-cost.

2.1.1. GENERAL FEATURES

- Measurements: Phase-currents. Differential currents, restraint currents. Positive, negative and zero sequence of currents of each winding. Power calculated from the magnitude of current and voltage: active, reactive and apparent power. Frequency. Thermal image.
- Measurement accuracy:

Measured currents (phases)	+/- 0.1 % or +/- 2 mA (the greater)
Measured currents (ground)	+/- 0.1 % or +/- 1 mA (the greater)
Measured voltages	+/- 0.1 % or +/- 50 mV (the greater)

  - Active and reactive powers (In=5A and Iphases>1A)
    - +/- 0.3% (0º or +/-90º or 180º)
    - +/- 1% (+/-45º or +/-135º)
    - +/- 5 / 0.5% (+/-75º / +/-115º)
- Fault reporting. Capacity of storing up to 15 fault reports with relevant data.
- Oscillographic recording. The oscillography record allows up to 64 oscilographs to be saved in a cyclical memory
- Time Synchronization. Via GPS (IRIG-B protocol) or by communications through the remote communications port.
- Communication ports. The relay can have up to five remote communication ports.
  - Local: RS232+USB front panel ports
  - Remote:
    - Up to 3 non IEC 61850 (DNP 3.0, Modbus, Procome) ports which can be RS232/485, Ethernet and Fiber Optics.
    - Two choices for IEC61850 ports: either 2xRJ45 100TX ports or one Fiber Optic MTRJ port.
- Power supply: 48-250 Vd.c./Va.c. (+/- 20%)
- Current circuit burden < 0.2 VA
- Voltage circuit burden < 0.55 VA
- Power supply burden: quiescent 7 W, maximum < 20 W

- Breaker trip and close outputs and auxiliary outputs:
  - I DC maximum limit (with resistive load) 60A (1s)
  - I DC continuous service (with resistive load) 16 A
  - Breaking capacity (with resistive load) 110 W (80 Vdc-250Vdc)
  - Break (L/R 0 0.04 s) 120 W at 125 Vdc
- 1000-record-capacity sequence of events log stored in non-volatile memory.

2.1.2. PROTECTION FUNCTIONS

This is the list of protection features provided by IRV platform:

- Two instantaneous phase overcurrent units (A;B;C) (50P)
- Two instantaneous negative sequence overcurrent units (I2) (50Q)
- Two instantaneous neutral overcurrent units (N) (50N)
- One instantaneous sensitive neutral overcurrent unit with independent analog input (Ns) (50Ns)
- Three time delay (inverse/definite) phase overcurrent units (A;B;C) (51P)
- Three time delay (inverse/definite) negative sequence overcurrent units (I2) (51Q)
- Three time delay (inverse/definite) neutral overcurrent units (N) (51N)
- One time delay (inverse/definite) sensitive neutral overcurrent unit with independent analog input (Ns) (51Ns)
- Three overcurrent units with voltage restraint. (51V)
- One directional phase overcurrent unit (A,B,C) (67)
- One directional neutral overcurrent unit (N) (67N)
- One directional ungrounded neutral overcurrent unit (Na) (67Na)
- Three undervoltage units (selectable input L-L or L-N) (27)
- Three overvoltage units (selectable input L-L or L-N) (59)
- Two neutral overvoltage units calculated from the phase voltages (59N)
- Three over frequency units (81M)
- Three under frequency units (81m)
- Recloser (79)
- Synchro-check unit with voltage, phase and frequency elements. Includes programmable logic based on bus and line conditions (25)
- Directional power unit (active/reactive) (32P/Q)
- Thermal image unit (49)

- Breaker Failure unit (50 BF)
- Phase unbalance unit (I2/I1) (46)
- Restrained earth fault unit (87N)
- Phase angle measuring unit (out-of-step) (78)
- Four derivative of frequency units (87D)

2.2. MGCC – CPT according to ZIV’s denomination

CPT belongs to a family devices designed to function as Substation Central Units, Transforming Station Central Units and/or RTU's, resolving communications and data handling requirements for protection, control and metering devices in electrical installations.

The CPT is designed to solve all communication and data processing needs with a substation’s protection, control and metering equipment, providing new functions that make most of the information available to these units. The CPT is responsible for communications with level 1st equipment and for real-time database maintenance, incorporation of automatic devices and logic at substation level being possible.

CPT relays are also provided with a web server to access the Integrated Web Console (built into the CPT itself) that can at the same time be accessed via web client from any substation computer, serving the purpose of interface between user and system.

On the other hand, CPT relays can be used to establish communications with the remote control office or SCADA.

The CPT terminal facilitates the migration process through the newest substation automation systems, allowing the integration of new communications standards in existing systems. For example, their design allows them to function as both the "client" and the "server" in systems with a communications architecture based on the IEC61850 standard, where the protection, control and metering devices are interconnected through an Ethernet network.

The entire system can be configured through specialized software developed by ZIV. These programs enable the system to be configured to adapt to the stations’ characteristics: equipment connected, signals associated with each unit, representation of the information on displays, logic functions at the substation level, desired functionality, etc.

Figure 2-4: CPT model

Figure 2-5: View of one of CPT installed in the demonstrator

2.2.1. Functions

The main functions of the CPT devices are described below:

- Substation & transforming station IEC61850 client, controlling communications with various protection, control and metering devices.

The CPT can also communicate with the protection, control metering equipment through other standard protocols like PROCOME, DNP 3.0, MODBUS, IEC 102 and IEC 103.

- IEC61850 server, with the corresponding data and services model, including gooses.
- Execution module for system central programmable automation and logic. The CPT has an internal task responsible for executing a fully programmable logic program by means of certain functions: logic gates (AND, OR, NOT, etc.), flip-flop (RS, JK), commands, etc.

This logic program may be used to implement control functions at the substation & transforming station level, group signals to send to the control office, etc.

- High level communications management (Control Center). It also communicates with the control station, emulating the necessary protocol in each case, to inform the same of the events occurring at the substation and enable it to manoeuvre on its active elements.

The CPT allows commands to be executed on the installation's configurable elements. The command may originate internally (control functions, logic) or externally (operating console, control center). The CPT modifies the format of commands between the different protocols so that the command reaches the equipment that must execute it, regardless of the manufacturer of the equipment. Likewise, it closes the communication loop, if the communications protocol supports this, by sending the unit’s response to an order to the equipment from which the order originated.

There is a blocking logic that prevents performing dangerous or forbidden manoeuvres in certain situations.

- Communication concentrator designed for the Automatic measurement of electric energy meters, being in this case the transforming station its natural location.
    - Up to 800 single-phase or three-phase meters.
    - Support the international standard IEC 60870-5-102. Communications through PLC with an additional link level.
    - Redundant local meter
    - Keeps the meters synchronized
    - Detects automatically the connection of new meters to the network
    - Serves as a bridge between the meters and the network operator LAN.
    - Stores:
        - Identification meter data (serial number)
        - Meter network management data (connected phase, date of last Communication, repeaters, etc...)
        - Consumed energy from all meters (actual values)
        - Consumed energy from all meters (last end of billing period). Communication devices:
- Allocation of local and remote agents for automated local operation by means MSMQ and WEB service.
- Management of local and remote communications using the ZIV HMI.
- Generation of databases in real time of all substation variables: alarms, measurements, status, controllers, etc. The CPT collects data from the substation’s IED, control and

metering units and maintains a database with this data, updated in real time. This database is the data medium for the HMI (local and remote) and all other internal tasks or applications communicated with the central unit, such as control centers, etc.

- Event Management. Information of the level 1 equipment is collected by first asking for a “snapshot” of the status of all signals available in the equipment, and afterwards spontaneously by data/quality change or asking for changes in these signals in a cyclical manner. All of these changes are sent to the internal tasks that have requested this information from the database.
- However, not all signal changes occurring at the substation will be useful to the user; in other words, not all will be defined as events. The CPT filters and sends to the HMI module those changes that the client considers interesting.
- Similarly, each database client task will receive all signal changes collected from the equipment, and it will be its job to filter them, keeping those that are to its interest and discharging those that are not.
- Alarm Management. The same as with the events, not all signal changes are alarms. The CPT is responsible for managing the alarms occurring at the substation, indicating the HMI module which of the changes that have been sent are alarms and which are not.
- Alarm management for the control office is one of its tasks; the only thing the CPT does is filter the changes and send along only those that are of interest.
- Control Functions. The CPT can execute certain control functions at the substation level, in which signals from different equipment take part. These control functions can be of two types: fixed or programmable.
- The former category includes those whose functionality is fixed and cannot be altered; they may only be configured and set. The latter includes those that are programmed within control logic.
- Log/trends Management. Another optional functionality of the CPT is to log changes in signals, measurements and meters. These logs are daily records, saved on disk, of the information you wish to save.

- Substation configuration management module, in charge of keeping the system SCD file updated in terms of the CID files for the associated IED's.

- FTP server.

- Client/Server Service for SNTP clock synchronization protocol. Furthermore, the CPT has an interface to obtain the standard GPS clock signal, with the ability to, on the one hand, receive the signal delivered directly through a GPS antenna, and on the other hand, also offer a connection to a GPS receiving device.
- The CPT can be responsible for keeping the entire system synchronized with a single clock source. This source may be external or internal. If external synchronization is not possible, the CPT uses the internal real-time clock (RTC) as a standard to synchronize the clocks of the different equipment connected to it.
- Redundant operational modes:
  - Capability to function on a redundant communications network (topology in double star and double ring).
  - Capability to function with a second Reserve Central Unit in Dual mode or in Hot-Stand-By mode.
- Local and remote HMI (console), web server based.
- Gateway between conventional systems and IEC61850 systems.
- Integrated simulator for signals, measurements, controllers and control orders.
- Self-checking. The central unit periodically checks the integrity of the hardware and the software stored on its permanent memory devices. It also has a system that picks up any error that occurs when the unit's hardware is accessed, so that the system can continue operating in an emergency mode if necessary, until the problem can be solved.
- Human-Machine Interface. There is an operator interface that allows obtaining information regarding the equipment's functionality, as well as information that will enable the supervision of the central unit's performance and operability at all times. This interface has an LCD display, a keypad with basic functions and a series of configurable LEDs which show the status of certain system control signals.

All of these features make the CPT a powerful machine that combines all of the functionality of an HMI and RTU Substation Central Unit into one device. The CPT can also function with each function segregated into independent machines.

2.2.2. SW Architecture

The software of the CPT comprises of five distinct modules:

- Real-Time Operating System for embedded-type architecture.
- Implementation of the real-time database configured in the system, automatics and programmable logic.
- Multi-agent module
- Communications module with the Local Operation Console of the substation installed on the HMI's PC.
- Communications libraries: protocols IEC61850, IEC60870-5-102, IEC60870-5-104, MODBUS,....

The operating system of the CPT is installed in the unit's internal flash memory, while the application and the remaining modules are installed in the device´s removable Compact Flash memory.

2.2.3. Communication protocols

- Complete TCP/IP protocol and communications for 802.3 (LAN) wired networks.
- IEC61850 communications module:
    - Common data models, compatible and extended (IEC61850-7-3 and IEC61850-7-4) and ACSI Services (IEC 61850-7-2) for Clients, MMS protocol mapping (ISO/IEC 9506 Part 1 and Part 2) and ISO/IEC 8802-3 Ethernet.
    - GOOSE services.
    - SNTP protocol clock synchronization.
    - Configurability of XML files according to SCL templates (IEC 61850-6: Substation Configuration Language).
- Modules with typical asynchronous serial protocols for communication with bay devices (level 1): PROCOME, DNP3.0, IEC 870-5-102, IEC 870-5-103, MODBUS, etc.
- Modules with asynchronous serial protocols for communications with the control center: IEC 870-5-101, IEC 870-5-104, DNP3.0, etc.

2.2.4. HW Architecture and Communication Interfaces

CPT terminals are equipped with industrial range specifications and feature a high level of reliability. Each CPT unit is mounted in a 19” rack and two units high, or half rack wide and panel mounted with three rack height units tall.

External connections use plug-in terminal blocks on the rear panel of the enclosure. The enclosure is provided with a ground terminal. It is essential that this terminal is properly connected to the substation or transforming station ground, to enable correct operation of the filters protecting IED from external electromagnetic disturbances.

The unit includes terminals for auxiliary voltage supply of 110Vdc / Vac (±20%). In case of power supply failure, a maximum interruption of 100ms is allowed for 110 Vdc input.

The hardware features (as minimum) are as follows:

- CPU card with a 533MHz microprocessor with industrial temperature range.
- 128 Mbytes of RAM.
- Internal memory of 16 Mbytes Flash.
- Compact Disc-Flash removable 256 MB (expandable).
- 2 type 100Base-T Ethernet ports for network connection according to IEC-61850 and 1 type 100FX Ethernet port for connection to the network using IEC-60870-5-104 (for communication between substations and Remote Control).
- Modems PLC. Two types of PLC Modems are used:
    - Type 1: Three PLC modems, A band (carrier of 80 kHz), connected each to one of the three phases of the LV network. They are used to communicate the 4CCT with the meters hanging from these phases.
    - Type 2: Two modems PLC, A band (carrier 66,6 kHz), with a BNC connector to link the 4CCTand other computer systems using the distribution medium voltage network.
- Coaxial connector for IRIG-B123 signal.
- 8 digital inputs and 8 digital outputs.
- 2 serial ports and two fiber optic RS-232 serial ports.
- USB port master.

- Front MMI (Keyboard and Display) and LEDs.

They also offer a wide range of communications channels, such as:

- Plastic and glass fiber optic asynchronous serial channels (ST, F-SMA connectors, etc.).
- Electrical asynchronous serial channels (RS-232C and RS-485).
- A general purpose serial communications channel (RS-232C).
- Two Ethernet ports, 10/100 BaseT (RJ-45).
- Optical Port: Supports IEC 60870-5-102 protocol
- A BNC port with IRIG-B123 signal decoder for clock synchronization.

2.3. Substation Hardened Ethernet Switch – SWT according to ZIV's denomination

The SWT, manufactured by uSysCom, a company of the ZIV Group, is an Ethernet Switch model designed to operate in environments with large electromagnetic fields or other adverse conditions.

uSysCom switches fulfil all the required functions to set up a reliable network within an electrical substation. SWT switches have the right double port configuration to set up any of the topologies a network architect could imagine.

Figure 2-6: SWT model

2.3.1. Main features

- IEC61850 certified: IEC61850-3 hardware environmental requirements. IEC61850 functional requirements.
- Modularity in number and type of ports. Different combinations in number and type of copper, multimode fiber and single-mode fiber in 10/100 Mbps and 1000 Mbps ports.

- DHCP Relay and Option 82 Redundancy in power supply. Possibility to increase the switch availability by having a second power source in case the first one fails.

- Power over Ethernet enabler. uSysCom switches can directly power up any PoE enabled device following the 802.3af standard. This way an IP phone or a wireless access point, can be powered with the same cable that is used for data transmission.

- Failure contact alarm. Hardware contact that is activated when a link problem occurs.

- Logs and alarms.3SWT creates logs where statistics about link status alarms are stored with the accurate timestamp, so all events can be traced.

- Advanced security features. 3SWT has advanced security features implemented to avoid unauthorized access to the system. It has different user levels with different passwords, the possibility to work with different VLANs, following the 802.1Q standard, port security based on MAC addresses, possibility to disable unused ports, authentication protocols.

- High Speed implementation of RSTP and MSTP. In high availability networks it is important to have a fast path recovery when any failure occurs. 3SWT not only follows the STP and RSTP protocols, but also exceeds the usual recovery time of these protocols due to its high speed implementation of RSTP, which grants fault recovery times lower than 4 ms. per link, always fulfilling the RST protocol.

- SNMP management. Easy integration of monitoring tools and alarms notifications in an SNMP based central management system, such as HP Openview.

- NTP client. 3SWT internal clock can be synchronized from a network SNTP/NTP server, so all time stamped events can be referenced from a reliable time reference.

- Port bandwidth limiting. 3SWT allows the limitation on bandwidth accepted for unicast, broadcast, multicast, or all type of traffic per port. This way, resources for non critical services can be limited.

- Broadcast Storm Control and IGMP snooping. Limiting broadcast traffic grants that no malfunctioning device saturates the network with undesired and uncontrolled broadcast traffic.

- Port mirroring. User can configure one port to replicate traffic flows of different ports, so the system administrator can monitor the incoming, outgoing, or all kind of traffic that is going through the ports under study.
- Statistics. User can access the traffic statistics per port live.
- Quality of service. User can define different priorities for different ports, so critical traffic is dealt with first.

2.3.2. APPLICATION FIELDS

- Reliable architecture. Network topologies within the electrical substation may vary depending on the number of services, number of substation cabinets, and number of different networks the electrical company would like to define. 3SWT switches have the right double port configuration to set up any of the topologies a network architect could imagine. The typical architectures within substations are stars, double stars, rings, double rings, and concatenated rings.
- Grouping services. It is convenient for electrical companies to have the different services within the substation separated and not accessible one from the other. In order to achieve this separation of traffic, different VLANs per service can be used. This way, different company departments will have access to their VLANs, and hence, only to the devices and equipment, under their own responsibility.
- Critical Services. The services running in an electrical substation may be different in importance. It is not the same to have IP telephony as it is to send orders to open a breaker. Using the quality of service feature for the different services allows electrical companies network architects to identify the critical services within the substation, warranting that all that traffic is treated with the adequate priority.
- GOOSE management. Above all the critical traffic in an IEC-61850 substation, you have the GOOSEs traffic, which can be tripping orders from protection relays. 3SWT is designed to treat that special traffic as its highest priority, so, even when the network is congested, a GOOSE will reach its destination in less than the time defined (4-10 ms depending on the performance class) in the IEC-61850 standard.

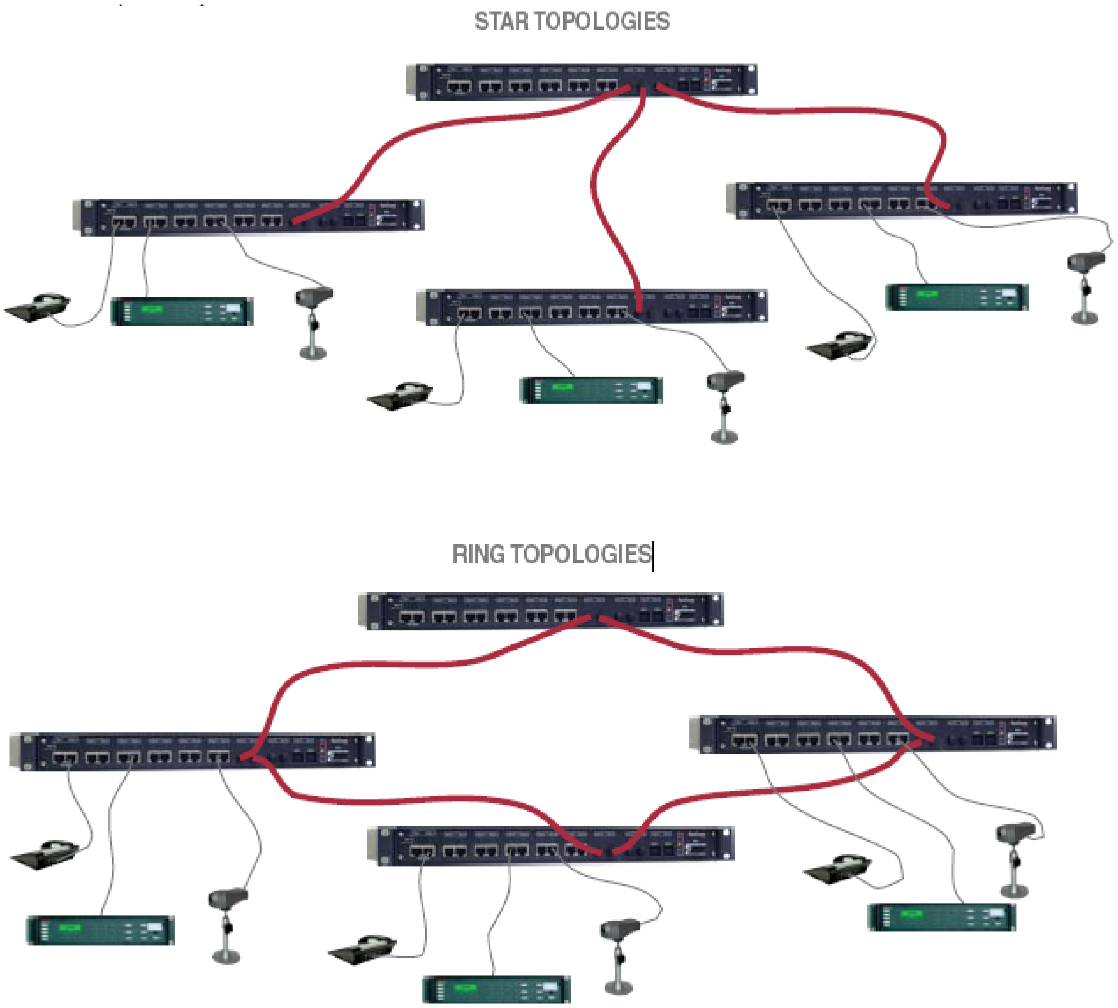


Figure 2-7: Most standard communications topologies based on switches

3. Communications Architecture

Selected communications architecture for the demonstrator is based on the “simplicity” concept. Deployed network architecture is a **simple star**, perhaps one of the simplest topologies for ETHERNET networks, but undoubtedly according to LABEIN’s microgrid architecture.

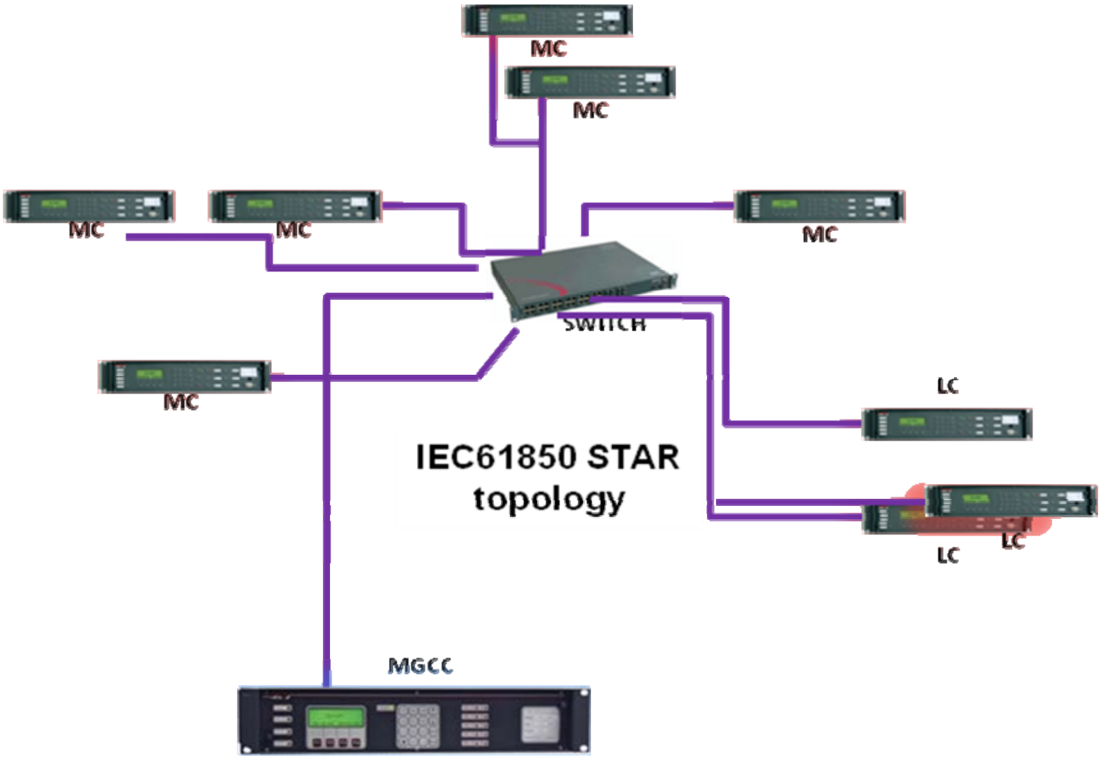


Figure 3-1: Star topology in the demonstrator for IEC61850 communications network

A star network has no redundant physical paths or loops in the network. The key benefit of a star topology is simplicity. The star is the only topology that can operate with unmanaged switches since it does not require any type of routing protocol. Since unmanaged switches are simpler electronic devices that have no CPU or software they might be considered more reliable. Use of unmanaged switches also reduces OAM overhead for the network since the LAN has no configuration or administration.

The disadvantage of a simple star topology is the lack of network path redundancy. Any single point of failure of a cable, switch port, or entire switch will interrupt a network path with subsequent loss of automation functionality. Because of the lack of any redundancy, the simple star is not recommended for substation automation. However, the star may be suitable topology when there are two separate networks in a redundancy, e .g an A+B protection system as shown in the following Figure 3-2.

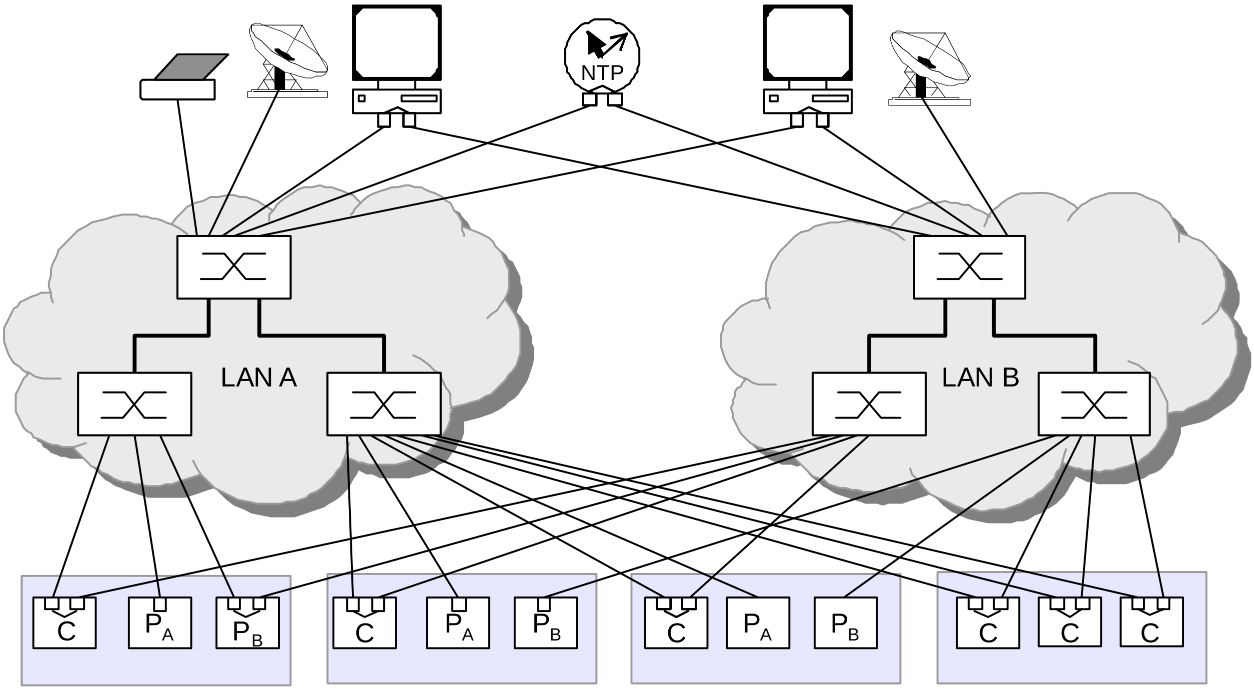


Figure 3-2: Redundant Star Topology

In fact, equipments used for this demonstration are able to support many other communications topologies. They are able to support from stars to rings, and also different redundancy configurations and protocols.

Probably, a very good alternative as communications architecture for microgrids will be in the future what is called “ring of IED switching end nodes“. Figure 3-3 shows a structure in which the IEDs are switching end nodes. This topology has the advantage to be resilient against any single link failure and some switch failures, and also very important, no need to have external switches (cost saving). The disadvantage is that is requires IEDs with a double network attachment and that the propagation delays are a bit large, as is the case in any ring. In such configurations it is advantageous that the IEDs use cut-through, although this does not improve the worst case delay.

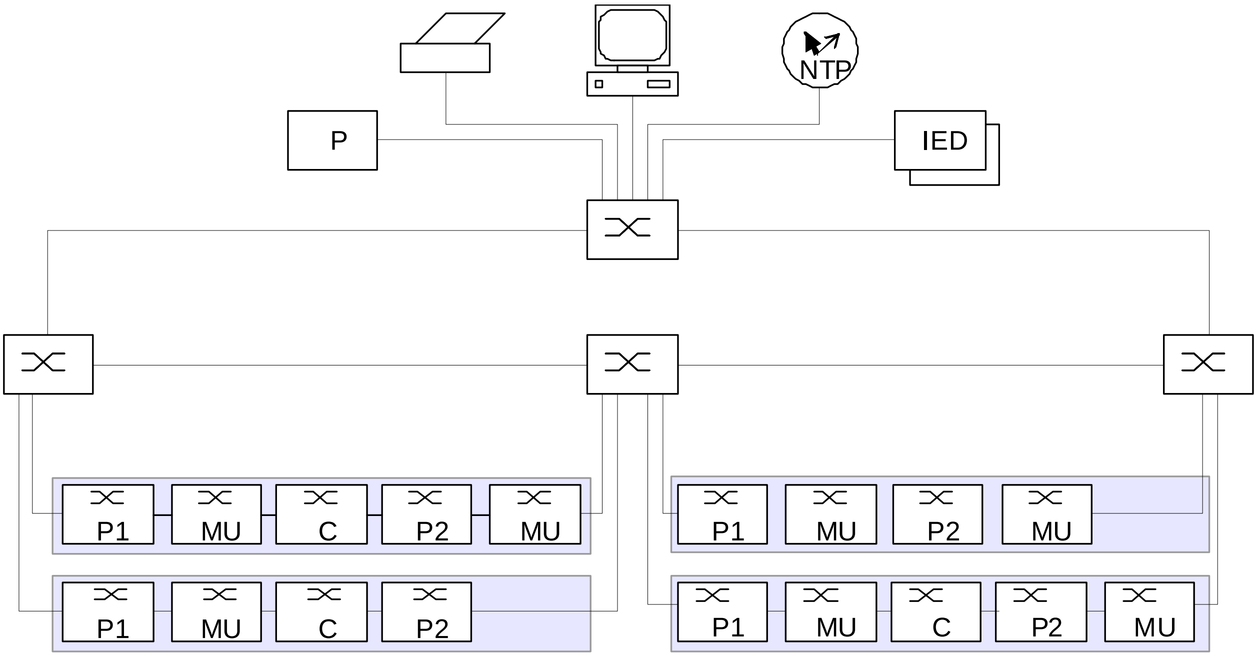


Figure 3-3: Ring-Ring-IED Topology

4. System Configuration

In this section specific configuration of installed IEDs is explained. Basically configuration work was done for MC and LC equipments, because the protection architecture selected was one decentralized.

Taking advantage of the protocol, more accurately, of standard IEC61850, it’s possible to coordinate all MC an LC between them and with any other protection in the MV/LV substation without any central equipment. IEC61850 provides a communications service called GOOSE that is a type of message that allows interchanging data directly between “equals”. With this operation principle, equipment with MGCC role is not necessary for protection purposes; certainly it will be necessary as IEC61850 client in order to act as local HMI or remote control gateway.

4.1. Configuration and Logic

First of all, from analogue data acquisition point of view, all IRVs (MC/LC devices) were installed using sensors (toroidal CTs) to acquire the currents to be measured. In the following table (Figure 4-1), within column TI, transformer ratios can be seen for each position.

Voltage acquisition didn’t require the use of intermediate PTs because IED’s voltage analogue inputs are able to withstand rated voltage (220Vca) in permanence.

Digital inputs are also used to get information about the status of each generator or load. In all cases only one digital input, number 3, is used; apart from the device installed in the network simulator that has configured two inputs, the second one to detect if microgrid is connected to utility’s network and the third one to determine if microgrid is connected to the network simulator.

So summarizing, with regard to the external connections configuration, phase and neutral currents, phase voltages and status of microgrid’s resources are obtained by wiring. Basically these are all data needed to perform the protection logic of a microgrid.

There is an additional logic implemented that is intended to substitute the information obtained by means digital inputs. It’s an OR logic of three comparators, each of them comparing a phase current with a minimum threshold, that determines if a generator is ON or

OFF, producing or disconnected. This way, protection system infrastructure can be even simpler saving the cost of cabling any digital input. See Figure 4-1 that depicts these details.

Posiciones	Tipo	Potencia	TI		DI		LOGIC1	LOGIC2	LOGIC3
Fuentes paralelo (Simulador de red)	N	100kW	300/5		DI2: "1" = isla IBERDROLA			DI	AND(LOGIC2 DI2+DI3)
					DI3: "1" = isla SIMULADOR RED		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Banco resistivo 1	L	150kW	300/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Banco resistivo 2	L	35kW	300/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Generador diesel 1	G	50kW	300/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Generador diesel 2	G	50kW	300/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Banco reactivo 1	L	33kVA	300/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Aerogenerador	G	6kW	100/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Fotovoltaica 1	G	3,6kW	100/5		DI3: "1" = Desconectado		I3f<25mA -- Desconectado	OR (DI,LOGIC1)	
Fotovoltaica 3	G	1,2kW (fase C)	100/5		DI3: "1" = Desconectado		Ic<25mA -- Desconectado	OR (DI,LOGIC1)	

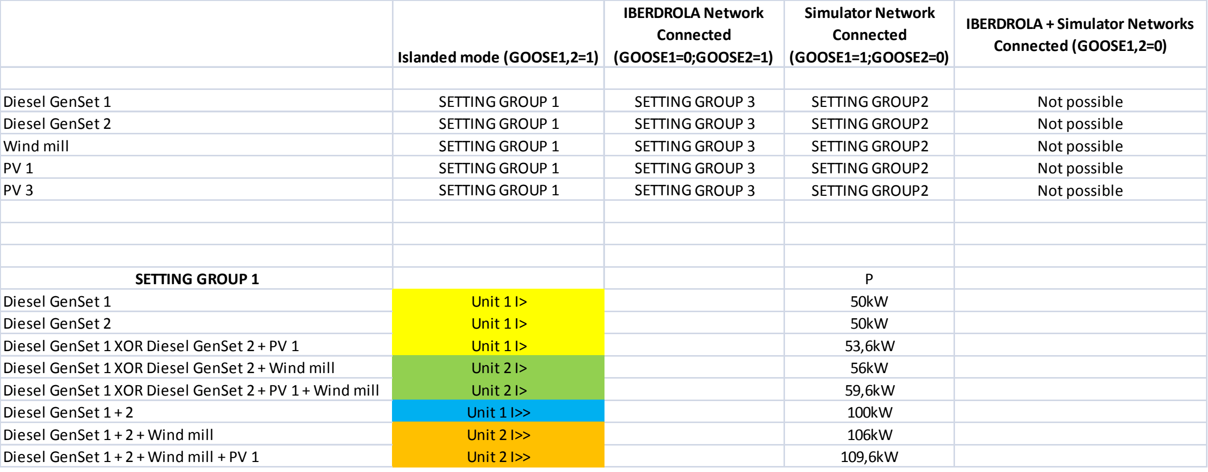
Figure 4-1: Basic configuration details for MC/LC IEDs

Fundamentally, the target of this protection system is to adapt to the changing conditions of the microgrid. Most important condition is if operating mode is “islanded” or “network connected”. Depending on this circumstance, protection parameters vary. Following the work done within WPC-TC2, adaptability of the protection system is based on setting groups and multiple instances of simple overcurrent units for each setting group.

In Figure 4-2 there is a table showing the possible operation conditions of LABEIN’s microgrid, where it can be connected to the utility network, to a simulation network or islanded. For each of these operating conditions, a different setting group will be used:

- Islanded: SETTING GROUP 1
- Simulation network connected: SETTING GROUP 2
- Utility network connected: SETTING GROUP 3

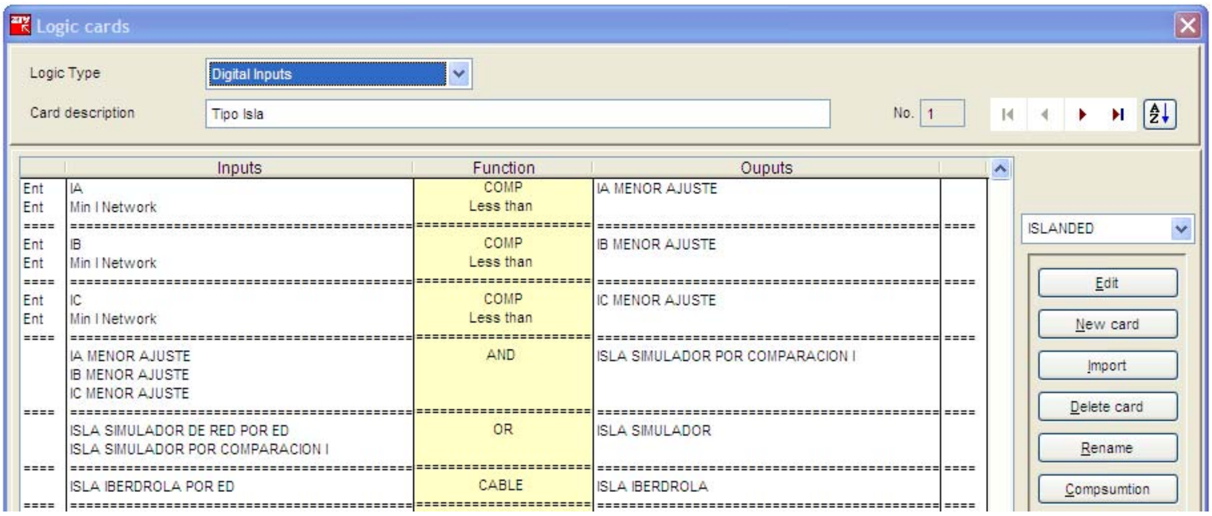
Basically, when microgrid is operating connected to an external network, it’s supposed that this external network is capable of providing enough short-circuit current to detect easily any internal fault. Nevertheless, when microgrid operates islanded from any external network, it’s supposed that protection system parameterization must consider which microgrid’s generation resources are running to tune itself. By this reason, logic configured in LABEIN’s demonstrator takes into account which generators are operating when microgrid is in islanded mode to activate or deactivate protection units with different pickup settings. In Figure 4-2 it’s shown how different units are used when setting group 1 is active, depending on the combination of generators that are producing energy.



	Islanded mode (GOOSE1,2=1)	IBERDROLA Network Connected (GOOSE1=0;GOOSE2=1)	Simulator Network Connected (GOOSE1=1;GOOSE2=0)	IBERDROLA + Simulator Networks Connected (GOOSE1,2=0)
Diesel GenSet 1	SETTING GROUP 1	SETTING GROUP 3	SETTING GROUP2	Not possible
Diesel GenSet 2	SETTING GROUP 1	SETTING GROUP 3	SETTING GROUP2	Not possible
Wind mill	SETTING GROUP 1	SETTING GROUP 3	SETTING GROUP2	Not possible
PV 1	SETTING GROUP 1	SETTING GROUP 3	SETTING GROUP2	Not possible
PV 3	SETTING GROUP 1	SETTING GROUP 3	SETTING GROUP2	Not possible
SETTING GROUP 1			P	
Diesel GenSet 1	Unit 1 I>		50kW	
Diesel GenSet 2	Unit 1 I>		50kW	
Diesel GenSet 1 XOR Diesel GenSet 2 + PV 1	Unit 1 I>		53,6kW	
Diesel GenSet 1 XOR Diesel GenSet 2 + Wind mill	Unit 2 I>		56kW	
Diesel GenSet 1 XOR Diesel GenSet 2 + PV 1 + Wind mill	Unit 2 I>		59,6kW	
Diesel GenSet 1 + 2	Unit 1 I>>		100kW	
Diesel GenSet 1 + 2 + Wind mill	Unit 2 I>>		106kW	
Diesel GenSet 1 + 2 + Wind mill + PV 1	Unit 2 I>>		109,6kW	

Figure 4-2: Configuration of IEDs for different operation modes

In Figure 4-3 it's shown the logic implemented in IED placed as MC for Network Simulator. This device is in charge of determining the basic status of the microgrid, islanded, utility connected, simulator connected.

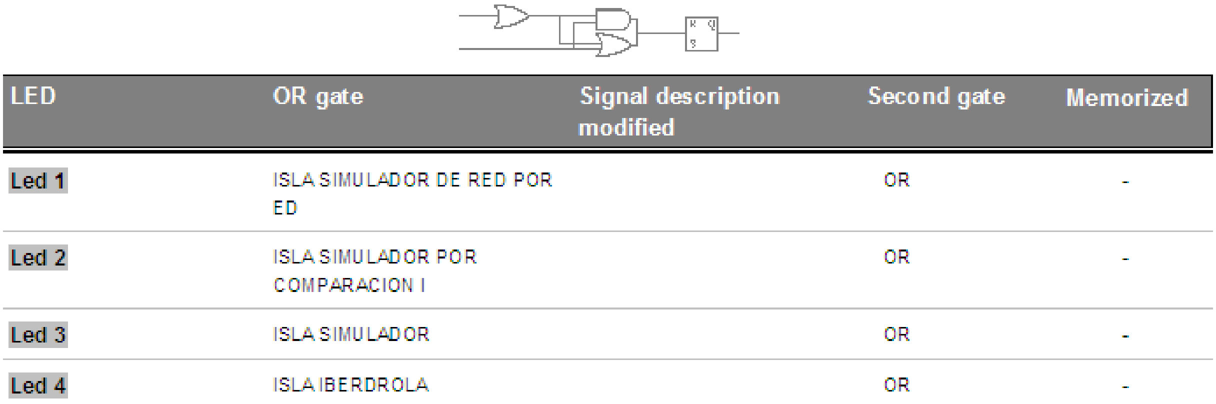


Logic Type: Digital Inputs
Card description: Tipo Isla
No. 1
ISLANDED

	Inputs	Function	Ouputs
Ent Ent	IA Min I Network	COMP Less than	IA MENOR AJUSTE
Ent Ent	IB Min I Network	COMP Less than	IB MENOR AJUSTE
Ent Ent	IC Min I Network	COMP Less than	IC MENOR AJUSTE
	IA MENOR AJUSTE IB MENOR AJUSTE IC MENOR AJUSTE	AND	ISLA SIMULADOR POR COMPARACION I
	ISLA SIMULADOR DE RED POR ED ISLA SIMULADOR POR COMPARACION I	OR	ISLA SIMULADOR
	ISLA IBERDROLA POR ED	CABLE	ISLA IBERDROLA

Figure 4-3: Deployed logic in MC for Network simulator

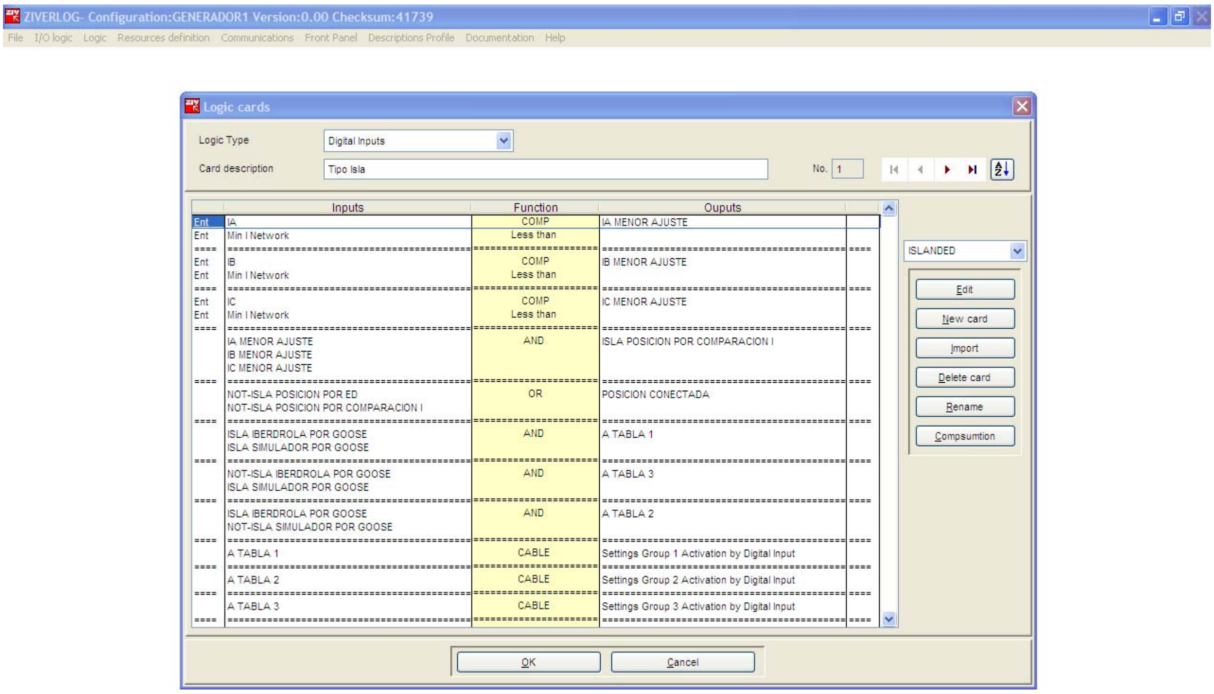
And in order to provide an easy way to see the behavior of the protection system, and due to the fact that none of these equipments can command any circuit breaker, LEDs on the front panel were selected to reflect the parameterization changes of each IED. So, in Figure 4-4 it's shown the configuration for LEDs in Network simulator's MC.



LED	OR gate	Signal description modified	Second gate	Memorized
Led 1	ISLA SIMULADOR DE RED POR ED		OR	-
Led 2	ISLA SIMULADOR POR COMPARACION I		OR	-
Led 3	ISLA SIMULADOR		OR	-
Led 4	ISLA IBERDROLA		OR	-

Figure 4-4: LEDs configured in Network simulator’s MC

For the rest of MCs, logic configuration is basically the same but different from the Network simulator’s one. In Figure 4-5 it’s depicted the logic of one of Diesel generators, but it’s absolutely equivalent for the rest of MCs. This logic considers the status of microgrid, and in case of being islanded, also the status of other generators. Depending on the conditions, it forces a change to a different setting group, and even a change of active protection units (see Figure 4-6).



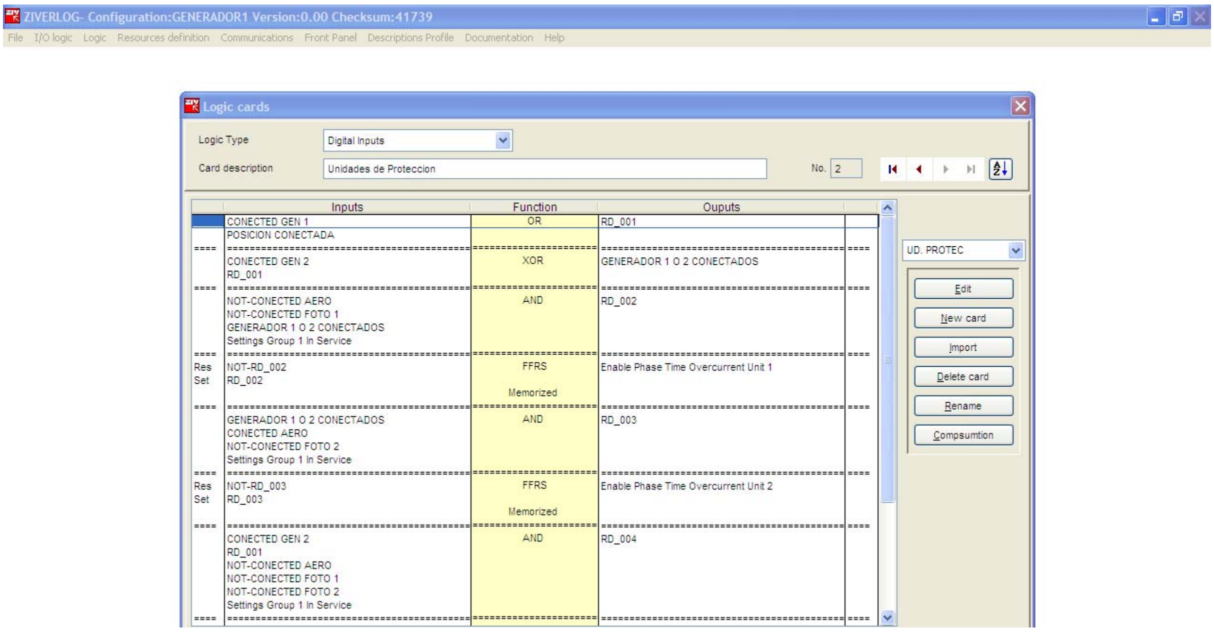
Logic Type: Digital Inputs

Card description: Tipo Isla

No. 1

	Inputs	Function	Ouputs
Ent Ent	IA Min I Network	COMP Less than	IA MENOR AJUSTE
Ent Ent	IB Min I Network	COMP Less than	IB MENOR AJUSTE
Ent Ent	IC Min I Network	COMP Less than	IC MENOR AJUSTE
	IA MENOR AJUSTE IB MENOR AJUSTE IC MENOR AJUSTE	AND	ISLA POSICION POR COMPARACION I
	NOT-ISLA POSICION POR ED NOT-ISLA POSICION POR COMPARACION I	OR	POSICION CONECTADA
	ISLA IBERDROLA POR GOOSE ISLA SIMULADOR POR GOOSE	AND	A TABLA 1
	NOT-ISLA IBERDROLA POR GOOSE ISLA SIMULADOR POR GOOSE	AND	A TABLA 3
	ISLA IBERDROLA POR GOOSE NOT-ISLA SIMULADOR POR GOOSE	AND	A TABLA 2
	A TABLA 1	CABLE	Settings Group 1 Activation by Digital Input
	A TABLA 2	CABLE	Settings Group 2 Activation by Digital Input
	A TABLA 3	CABLE	Settings Group 3 Activation by Digital Input

Figure 4-5: Example of logic for a Diesel GenSet’s MC



ZIVERLOG- Configuration:GENERADOR1 Version:0.00 Checksum:41739

Logic Type: Digital Inputs

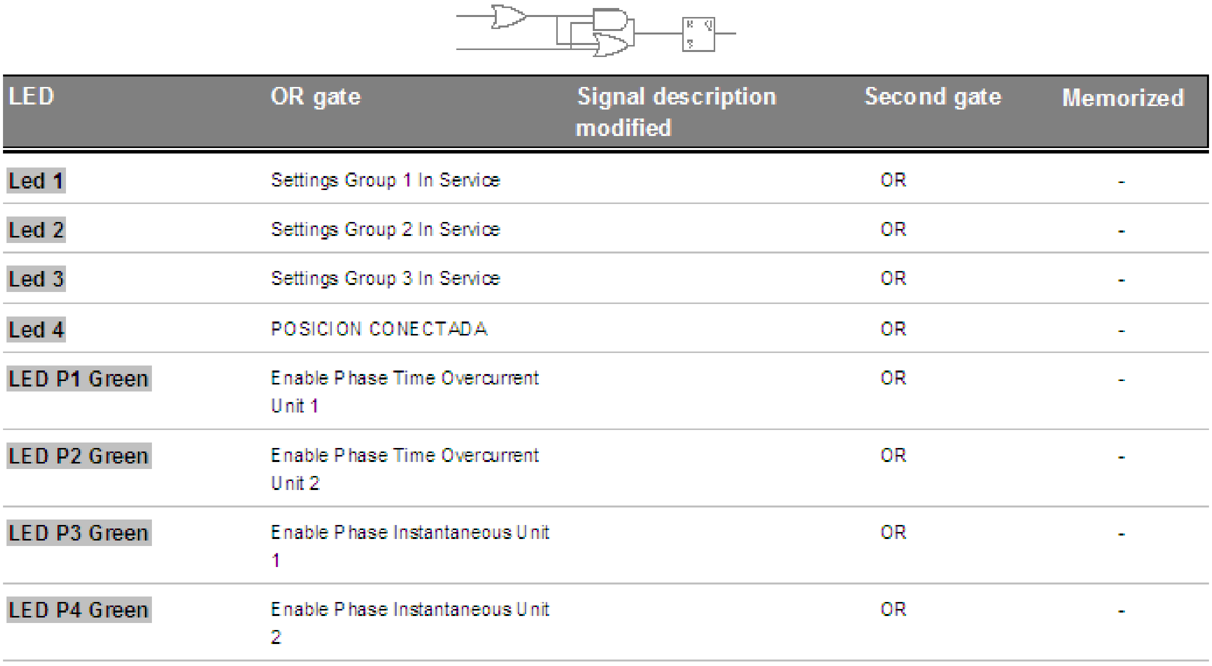
Card description: Unidades de Proteccion

No. 2

	Inputs	Function	Ouputs
	CONECTED GEN 1 POSICION CONECTADA	OR	RD_001
	CONECTED GEN 2 RD_001	XOR	GENERADOR 1 O 2 CONECTADOS
	NOT-CONECTED AERO NOT-CONECTED FOTO 1 GENERADOR 1 O 2 CONECTADOS Settings Group 1 In Service	AND	RD_002
Res Set	NOT-RD_002 RD_002	FFRS Memorized	Enable Phase Time Overcurrent Unit 1
	GENERADOR 1 O 2 CONECTADOS CONECTED AERO NOT-CONECTED FOTO 2 Settings Group 1 In Service	AND	RD_003
Res Set	NOT-RD_003 RD_003	FFRS Memorized	Enable Phase Time Overcurrent Unit 2
	CONECTED GEN 2 RD_001 NOT-CONECTED AERO NOT-CONECTED FOTO 1 NOT-CONECTED FOTO 2 Settings Group 1 In Service	AND	RD_004

Figure 4-6: Islanded mode. Change of active protection units

And in the same way that with the Network simulator's MC, the rest of MCs show their current protection configuration by means their LEds. In Figure 4-7 it's shown LED's configuration for MC assigned to Diesel generator 1.



LED	OR gate	Signal description modified	Second gate	Memorized
Led 1	Settings Group 1 In Service		OR	-
Led 2	Settings Group 2 In Service		OR	-
Led 3	Settings Group 3 In Service		OR	-
Led 4	POSICION CONECTADA		OR	-
LED P1 Green	Enable Phase Time Overcurrent Unit 1		OR	-
LED P2 Green	Enable Phase Time Overcurrent Unit 2		OR	-
LED P3 Green	Enable Phase Instantaneous Unit 1		OR	-
LED P4 Green	Enable Phase Instantaneous Unit 2		OR	-

Figure 4-7: LEDs configured in a Diesel Generator's MC

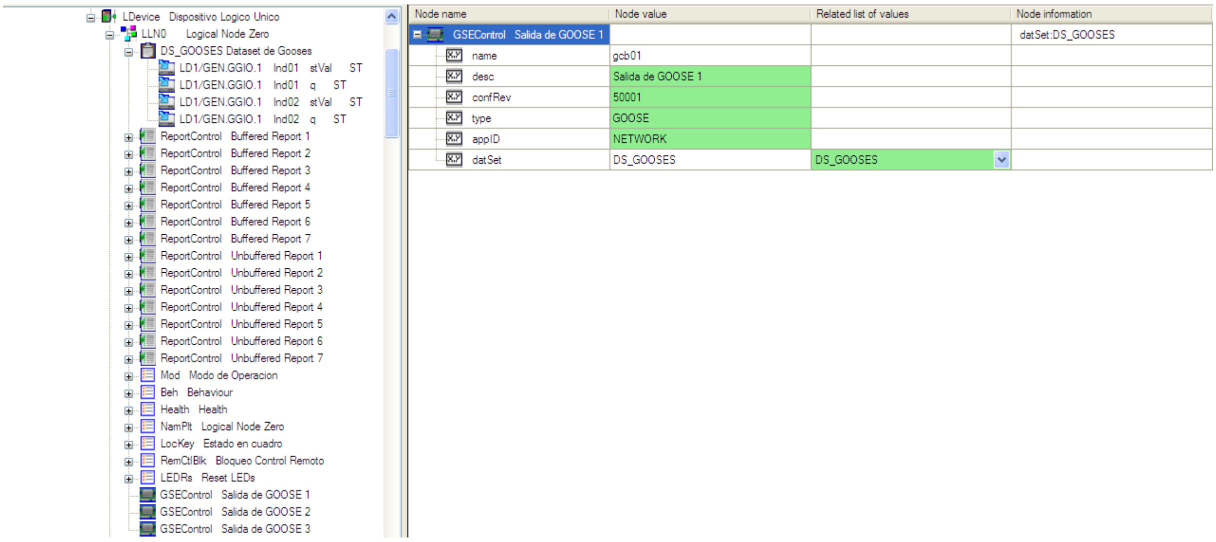
These two configurations represent the kind of logic implemented in all IEDs that are part of the adaptive protection system of microgrid.

4.2. IEC 61850 Configuration

A key element in this protection system is the communications standard used, that is IEC61850. This standard is very wide, but we just need to focus on GOOSE message to get an adaptive system.

This type of message is very fast, it is published by an IED and must be available for any possible subscriber in less than 4 milliseconds. Besides, any published message is available to any IED in the ETHERNET network because these GOOSEs are sent to a multicast address.

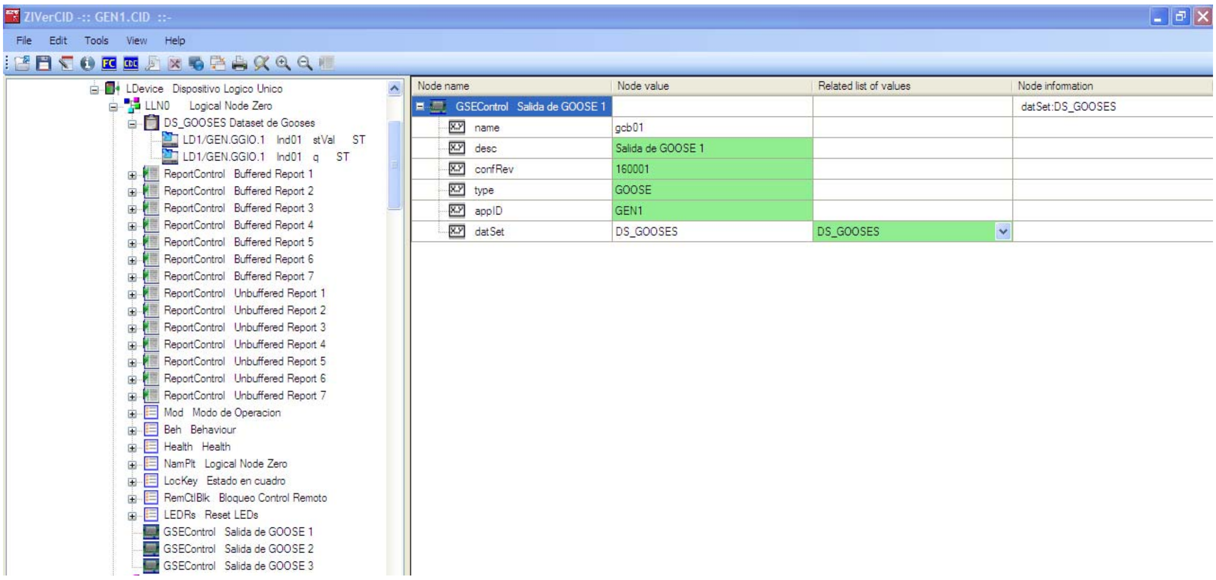
Concerning the configuration of MC/LC devices, basically they have configured as GOOSE OUT information about their status (connected or OFF – only one data [stVal+q], see Figure 4-9), except Network simulator’s one that configures two data (status with respect to utility network and simulator network), see Figure 4-8.



```
LDevice   Dispositivo Logico Unico
  LLN0   Logical Node Zero
    DS_GOOSES Dataset de Gooses
      LD1/GEN.GGIO.1   Ind01   stVal   ST
      LD1/GEN.GGIO.1   Ind01   q   ST
      LD1/GEN.GGIO.1   Ind02   stVal   ST
      LD1/GEN.GGIO.1   Ind02   q   ST
    ReportControl   Buffered Report 1
    ReportControl   Buffered Report 2
    ReportControl   Buffered Report 3
    ReportControl   Buffered Report 4
    ReportControl   Buffered Report 5
    ReportControl   Buffered Report 6
    ReportControl   Buffered Report 7
    ReportControl   Unbuffered Report 1
    ReportControl   Unbuffered Report 2
    ReportControl   Unbuffered Report 3
    ReportControl   Unbuffered Report 4
    ReportControl   Unbuffered Report 5
    ReportControl   Unbuffered Report 6
    ReportControl   Unbuffered Report 7
    Mod   Modo de Operacion
    Beh   Behaviour
    Health   Health
    NamPlt   Logical Node Zero
    LocKey   Estado en cuadro
    RemCtlBlk   Bloqueo Control Remoto
    LEDRs   Reset LEDs
    GSEControl   Salida de GOOSE 1
    GSEControl   Salida de GOOSE 2
    GSEControl   Salida de GOOSE 3
```

Node name	Node value	Related list of values	Node infomation
GSEControl Salida de GOOSE 1			datSet:DS_GOOSES
name	gcb01		
desc	Salida de GOOSE 1		
confRev	50001		
type	GOOSE		
appID	NETWORK		
datSet	DS_GOOSES	DS_GOOSES	

Figure 4-8: GOOSE OUT configuration for Network simulator’s MC



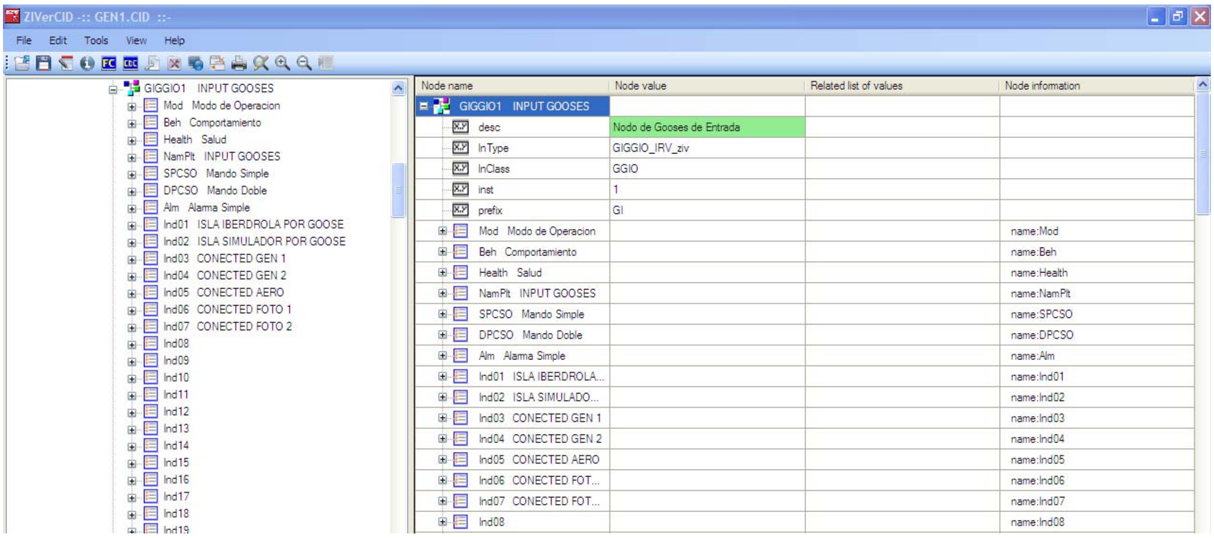
LDevice Dispositivo Logico Unico
LLN0 Logical Node Zero
DS_GOOSES Dataset de Gooses
LD1/GEN.GGIO.1 Ind01 stVal ST
LD1/GEN.GGIO.1 Ind01 q ST
ReportControl Buffered Report 1
ReportControl Buffered Report 2
ReportControl Buffered Report 3
ReportControl Buffered Report 4
ReportControl Buffered Report 5
ReportControl Buffered Report 6
ReportControl Buffered Report 7
ReportControl Unbuffered Report 1
ReportControl Unbuffered Report 2
ReportControl Unbuffered Report 3
ReportControl Unbuffered Report 4
ReportControl Unbuffered Report 5
ReportControl Unbuffered Report 6
ReportControl Unbuffered Report 7
Mod Modo de Operacion
Beh Behaviour
Health Health
NamPlt Logical Node Zero
LocKey Estado en cuadro
RemCtlBlk Bloqueo Control Remoto
LEDRs Reset LEDs
GSEControl Salida de GOOSE 1
GSEControl Salida de GOOSE 2
GSEControl Salida de GOOSE 3

Node name	Node value	Related list of values	Node information
GSEControl Salida de GOOSE 1			datSet:DS_GOOSES
name	gcb01		
desc	Salida de GOOSE 1		
confRev	160001		
type	GOOSE		
appID	GEN1		
datSet	DS_GOOSES	DS_GOOSES	

Figure 4-9: GOOSE OUT configuration for Network simulator's MC

In Figure 4-10it's shown the GOOSE IN configuration of Diesel Generator 1. GOOSE IN means which data an IED is subscribed to, and is the way for an IED to obtain information from other IEDs.

In this demonstrator all MC and LC, apart from the one in Network Simulator, configures seven data as GOOSE IN. These data include the operation condition of microgrid (islanded or network connected), and the status of other generators. An example of this can be seen in Figure 4-10.



GIGGIO1 INPUT GOOSES
Mod Modo de Operacion
Beh Comportamiento
Health Salud
NamPlt INPUT GOOSES
SPCSO Mando Simple
DPCSO Mando Doble
Alm Alarma Simple
Ind01 ISLA IBERDROLA POR GOOSE
Ind02 ISLA SIMULADOR POR GOOSE
Ind03 CONECTED GEN 1
Ind04 CONECTED GEN 2
Ind05 CONECTED AERO
Ind06 CONECTED FOTO 1
Ind07 CONECTED FOTO 2
Ind08
Ind09
Ind10
Ind11
Ind12
Ind13
Ind14
Ind15
Ind16
Ind17
Ind18
Ind19

Node name	Node value	Related list of values	Node information
GIGGIO1 INPUT GOOSES			
desc	Nodo de Gooses de Entrada		
lnType	GIGGIO_IRV_ziv		
lnClass	GGIO		
inst	1		
prefix	GI		
Mod Modo de Operacion			name:Mod
Beh Comportamiento			name:Beh
Health Salud			name:Health
NamPlt INPUT GOOSES			name:NamPlt
SPCSO Mando Simple			name:SPCSO
DPCSO Mando Doble			name:DPCSO
Alm Alarma Simple			name:Alm
Ind01 ISLA IBERDROLA...			name:Ind01
Ind02 ISLA SIMULADO...			name:Ind02
Ind03 CONECTED GEN 1			name:Ind03
Ind04 CONECTED GEN 2			name:Ind04
Ind05 CONECTED AERO			name:Ind05
Ind06 CONECTED FOT...			name:Ind06
Ind07 CONECTED FOT...			name:Ind07
Ind08			name:Ind08

Figure 4-10: GOOSE IN configuration for a Diesel Generator’s MC

5. Test Cases

The starting point of test cases is that simulation of short circuits is out of the scope of this demonstration, by two reasons:

- Danger of damaging resources of microgrid
- Lack of circuit breakers

Therefore, the type of test cases that could be executed in LABEIN's microgrid was basically to check if protection system adapts to microgrid's different operating conditions. In the following figures reaction of IEDs to different configurations are shown by means of the LEDs on the front panels.

Different operation modes were tested, from utility connected mode to network simulator mode, and finally islanded mode with some generators connected. In Figure 5-1 and Figure 5-2 we can see how, for example, network simulator measured currents and voltages when microgrid was fed by the network simulator.

Figure 5-1: Currents measurement in Network simulator's MC

Figure 5-2: Voltages measurement in Network simulator's MC

Test cases demonstrate that it's perfectly possible to implement a decentralized adaptive protection system just sharing by GOOSE ON/OFF status of microgrid's resources and the basic status of microgrid (islanded or not). The rest is done by a simple internal logic within IEDs.

5.1. GOOSE Traffic

This subsection just shows a capture of GOOSE traffic between MC/LC equipments for a specific circumstance, being highlighted the identification of the publisher and published data.

- Network simulator IED

```
IecSubscribe {
  goID = "NETWORK"
  gocbRef = "NETWORKLD1/LLN0$GO$gcb01"
  datSet = "NETWORKLD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 4
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 02
  t = 07/27/2009_18:34:01.000
  SqNum = 1150
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000],True,[0000000000000]}
}
# --------------------------------------
```

- Resistive Bank 2 IED

```
IecSubscribe {
  goID = "RESISBANK2"
  gocbRef = "RESISBANK2LD1/LLN0$GO$gcb01"
  datSet = "RESISBANK2LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 03
  t = 09/11/2009_23:01:53.000
  SqNum = 1069
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
```

```
}
# ---------------------------------------
```

- Diesel Generator 1 IED

```
IecSubscribe {
  goID = "GEN1"
  gocbRef = "GEN1LD1/LLN0$GO$gcb01"
  datSet = "GEN1LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 04
  t = 09/11/2009_08:31:08.000
  SqNum = 977
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# ---------------------------------------
```

- Diesel Generator 2 IED

```
IecSubscribe {
  goID = "GEN2"
  gocbRef = "GEN2LD1/LLN0$GO$gcb01"
  datSet = "GEN2LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 05
  t = 07/27/2009_12:36:37.000
  SqNum = 894
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# ---------------------------------------
```

- Reactive Bank 2 IED

```
IecSubscribe {
  goID = "REACTBANK2"
  gocbRef = "REACTBANK2LD1/LLN0$GO$gcb01"
```

```
  datSet = "REACTBANK2LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 06
  t = 09/12/2009_07:21:49.000
  SqNum = 824
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# ---------------------------------------
```

- Wind mill IED

```
IecSubscribe {
  goID = "AERO1"
  gocbRef = "AERO1LD1/LLN0$GO$gcb01"
  datSet = "AERO1LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 07
  t = 09/09/2009_09:22:23.000
  SqNum = 777
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# ---------------------------------------
```

- PV panel 1 IED

```
IecSubscribe {
  goID = "FOTO1"
  gocbRef = "FOTO1LD1/LLN0$GO$gcb01"
  datSet = "FOTO1LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 08
```

```
  t = 09/10/2009_00:22:39.000
  SqNum = 722
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# --------------------------------------
```

- Resistive Bank 1 IED

```
IecSubscribe {
  goID = "RESISBANK1"
  gocbRef = "RESISBANK1LD1/LLN0$GO$gcb01"
  datSet = "RESISBANK1LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 10
  t = 09/11/2009_22:40:13.000
  SqNum = 620
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# --------------------------------------
```

- PV panel 3 IED

```
IecSubscribe {
  goID = "FOTO3"
  gocbRef = "FOTO3LD1/LLN0$GO$gcb01"
  datSet = "FOTO3LD1/LLN0$DS_GOOSES"
  test = 0
  confRev = 0
  ndsCom = 0
  numDataSetEntries = 2
  VLANAppID = 0
  VLANVID = -1
  VLANPrio = 133
  dst = 01 0c cd 01 00 09
  t = 09/08/2009_09:44:47.000
  SqNum = 56
  StNum = 1
  HoldTim = 4000
  Data = {True,[0000000000000]}
}
# --------------------------------------
```

6. Conclusions

It can be stated that communications are a tool to set up adaptive protection systems that help to solve some of the biggest challenges at the time of protecting a microgrid, mainly when it's operated in islanded mode.

IEC61850 is a communications standard that provides very useful services that help to simplify these adaptive protection systems, because it offers point-to-point messages that minimize the wiring and assure the fastest response to the changes in microgrid's topology and operation conditions.

Communications architecture used is very simple and considerably cheap, but it could be even cheaper integrating the switches within IEDs. Anyway, technology used for IEDs and for communications is very common these days, allowing that these solutions prove to be very cost-efficient event for low voltage networks like the ones on microgrids.

Perhaps one critical issue are switching elements, because without them, microgrid's protection possibilities are drastically reduced.