Advanced Architectures and
Control Concepts for

MORE MICROGRIDS

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TF7: Field test of different Microgrid topologies at steady and transient state in ERSE microgrid

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EXECUTIVE SUMMARY

Within Work package F Task 7, the ERSE Distributed Energy Resources Test Facility (DER-TF) has been used to test different generators and storage systems, operating on a stable reference “virtual islanding” microgrid, obtained by the interposition of the I-POWER inverter (from Turbo Power System) between the “main grid” and the “microgrid” and to test the controlled transition from grid connected to “virtual islanding” operation and reverse.

This has resulted in the successful implementation of a fully flexible “virtual microgrid” under laboratory conditions, which has allowed the examination and investigation of several Microgrid topologies and generation scenarios under well defined steady state and transient network situations.

The main conclusions that have been reached by this task are that under non transition state conditions, Microgrids are well behaved and can usefully complement the network operation, however under transient conditions of transferring to and from grid for islanding operation, issues affecting overvoltage on the Microgrid can arise which leads to areas of concern.

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INTRODUCTION

The concept of a Microgrid is defined as a LV distribution system with distributed generation sources, storage devices, and loads operating as a single coordinated entity. It is therefore an inherently advanced grid architecture which will enable efficient integration of Distributed Energy Resources (DER's) into LV distribution networks and can be operated interconnected with other networks, which can be a mixture of other islanded or hybrid grid systems.

One of the major objectives of The MORE Microgrids project was to include a number of Microgrid architectures and experimentally validate these in interconnected mode, islanded mode and during the transition from one mode to another. The major aim of Work-package F within the MORE Microgrids project was then to actually demonstrate and validate the operation of these Microgrids in real life situations, bearing in mind the safety and comfort of the end user, i.e. the consumer.

Conditions were also realised that could potentially be unsafe, where real users come into contact with the Microgrid. To fully evaluate the usefulness of Microgrids, these conditions do need to be studied and the limits of safe operation explored. This was the target of Work-package F, Task 7 (WPF TF7), here, where the ERSE test site is a reference laboratory, the test site is able to fully emulate virtually any microgrid architecture, and to allow the realisation of conditions that could potentially be unsafe but could arise in practise. These conditions can be made repeatable, well defined and can be accurately measured by the generation and load systems and the data acquisition equipment installed at the facility. In addition the equipment is under the control of the laboratory operators and, if unsafe and unforeseen scenarios arise, appropriate safety procedures are already in place to minimise risks.

The task also involved testing of power electronics components, advanced storage interfaces, development, comparison and testing of new alternative control concepts and algorithms, development of interface and communication protocols and components. Attention was also paid to the requirements for the physical interconnection between micro-generators and the distribution grid, for example, voltage regulation, synchronisation, power quality, safety and EMC. On this issue, the EU has generally been running behind the USA where standardisation work has been carried out and produced standards such IEEE 1547 and ANSI-UL 1741. The results from MORE Microgrids have now contributed towards filling this gap and relevant results from MORE Microgrids will be automatically forwarded to the relevant active standardisation groups, where the engineers involved on WPF TF7 are also directly involved in assessing and writing International and National Standards and the DER-TF is being used to assess, verify and modify existing and proposed test procedures.

ERSE has performed several different experiments at its test facility for WPF TF7, the first under steady state conditions (i.e. an intentional islanded condition with a portion of the LV system not directly connected to the MV grid, but coupled through the back-to-back I-power inverter). Here Power Quality impact in terms of harmonics, flicker, voltage fluctuations and unbalance have been studied on both Microgrid and the “main Grid”; the investigation have shown the Microgrid have been greatly improved by the insertion of the isolating inverter. The conclusion reached on this series of experiments is that Microgrid operation can greatly enhance the performance of a local area network when external influences on either side of the Microgrid are taken into account.

This situation can arise in several real life scenarios, such as the strengthening of radial grid networks connected by spur lines without up-rating the connecting cable or dock side operations where an incoming ship has it's own generation system at a different frequency or voltage from the port at which the ship is berthed. Here the ship can be powered from the local network and will act as an independent Microgrid without having to run the on-board generation plant, thus reducing carbon emissions.

The same conclusion has been reached during transient state behaviour, here short-duration voltage variations for single/three phase AC faults, or dynamic response to sudden load changes and to conditions of phase imbalance or loss of phase, have been shown to have been improved by adopting a decoupled Microgrid approach. With local energy storage and generation Power Quality has been kept high on the side of the Microgrid not directly connected to the disturbance generation mechanism.

The final series of experiments involved studying the transition of the Microgrid from an islanded or isolated condition back to a grid connected state and vice-versa. Outwardly the transfers seemed to be satisfactory, however it was found that at short time-scales transient conditions arose that gave concern. Typically, on a transition from grid to islanding, a voltage dip of a cycle or so occurred on the Microgrid if prior to the transition there was a requirement for power to flow into the Microgrid, or more seriously a short term voltage spike was sometimes seen. On a transition from Islanding back to grid connected again, short term supply disturbances could be seen. These type of transients have also been reported and have caused damage on multiple inverter systems in Spain [1].

The project time scales and resources have limited the amount of effort available to investigate these potentially damaging problems, but it is suspected that what is happening is a timing and control issue as the mechanical by-pass breaker is changing state. When the by-pass breaker is in circuit, the I-Power inverter is configured as a four leg current mode inverter, ready for mode transfer, when an islanding condition or command is received, then the inverter has to re-configure itself into a four leg voltage mode inverter; the inverter, at present has no knowledge of the current flowing in the by-pass circuit or when the actual mechanical contacts will break. Thus the inverter has to take a 'best guess' at the conditions required to support the independent microgrid and quickly correct itself if there is a mismatch; mechanical breakers are not accurate in their drop-out time and it is this together with the power requirements mismatch that is thought to cause the voltage transients. This type of problem can arise in a real Microgrid and it is the intention of the partners to investigate this further as well as bringing it to the attention of the relevant standardisation committees.

1 ERSE DISTRIBUTED ENERGY RESOURCES TEST FACILITY (DER-TF)

The ERSE Distributed Energy Resources Test Facility (DER-TF) is a complete and well-structured system with several generators, controllable loads and storage systems, which can reproduce a real LV microgrid, connected to the MV grid through a transformer. The layout of DER-TF is shown in

All DERs are connected to the microgrid through an interconnection board that allows the microgrid operator to change configurations, thus obtaining different grid topologies (radial and meshed), the feeders of which can extend out to 1 km. The DER-TF can provide electricity to the main grid with a maximum electrical power of 350 kW. The interconnection board and all the DERs are provided with electrical measurement equipment, consisting of high-speed Data Acquisition Systems (DAS), which have been set up to collect and analyze the experimental data derived from the field tests. A communication system has been developed with different technologies: LAN Ethernet, Wireless and Power Line. All DERs are equipped with their local control systems and interfaced with a central supervision and control infrastructure that receives the measurements and sends commands and set-points to the DERs. It will also archive data and control functions, in order to be able to exercise the microgrid with user-defined optimization algorithms.

Within this project, the ERSE DER-TF has been used to test different generators and storage systems, operating on a stable reference “virtual islanding” microgrid, obtained with the interposition of the I-POWER inverter (from Turbo Power System) between the “main grid” and the “microgrid” and to test the controlled transition from grid connected to “virtual islanding” operation and reverse.

MORE Microgrids has several real life test sites, the ERSE test site is a reference laboratory, able to emulate a microgrid, allowing the realization of conditions that could potentially be unsafe where real users come into contact with the microgrid. These conditions can be made repeatable, well defined and can be accurately measured by the generation and load systems and the data acquisition equipment installed at the facility.

In addition the equipment is under the control of the laboratory operators and, if unsafe and unforeseen scenarios arise, appropriate safety procedures are already in place to minimize risks.

The engineers involved in this task are also directly involved in assessing and writing International and National Standards, and the DER-TF is being used to assess, verify and modify existing and proposed test procedures. The work performed in ERSE test site will feed directly into the relevant IEC and National Standards Committees.

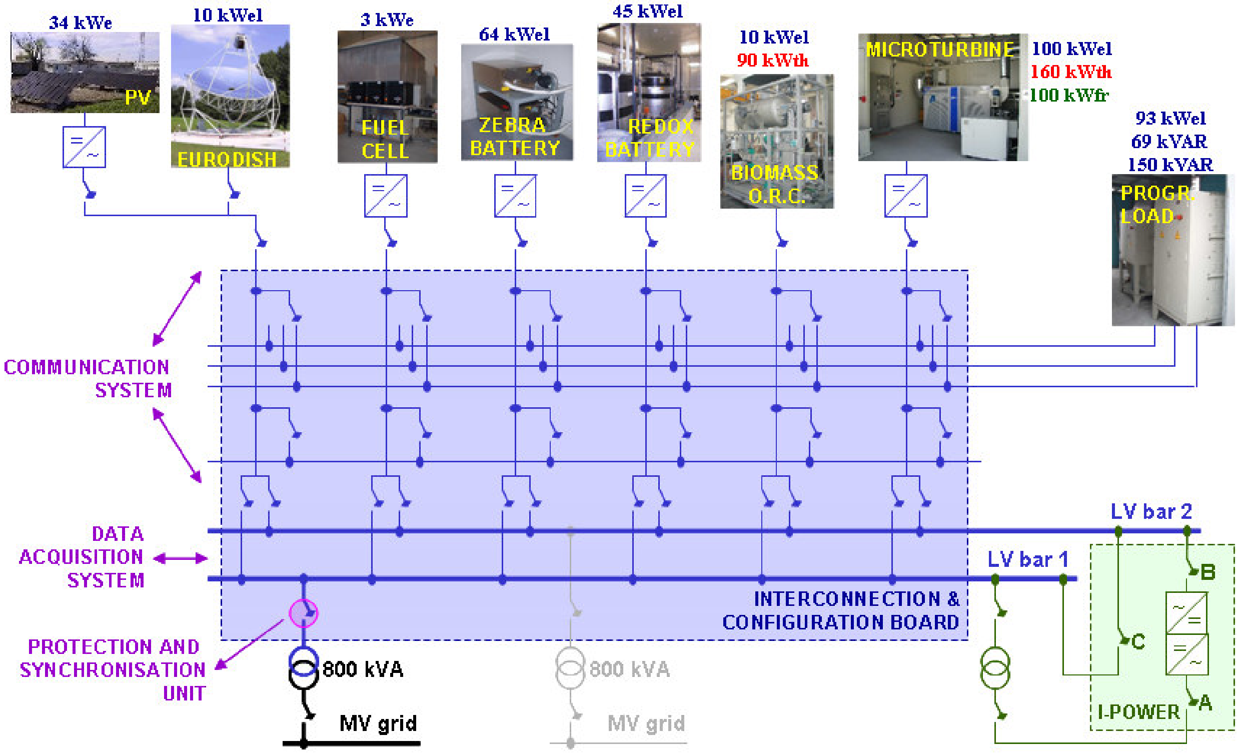


Figure 1.1 – Layout of ERSE Distributed Energy Resources Test Facility (DER-TF)

2 THE I-POWER CONVERTER

This document contains an overview of the ENT200 microgrid test system and the information necessary to connect the ENT200 microgrid test system into a microgrid network. The supplied system consists of two back to back inverters. One inverter is connected to the grid and supplies power to a DC bus. The other inverter converts the DC bus power to a three phase variable frequency, variable voltage output. The power supplied by the voltage source is up to 200kW at a power factor of >0.8. A bi-directional three phase inverter is used to transfer power to and from the main grid.

2.1 System overview

The incoming utility grid is transformed to an isolated nominal 415 V distribution grid. This supplies the local microgrid, which can contain several connected loads and distributed power generators. A by-pass breaker allows for direct connection of the LV distribution grid to the micro-grid. When the breaker is open, the inverter transfers power between the LV distribution grid and the micro-grid. In this situation it is possible to operate the micro-grid independently. The unit allows programming of different operating voltage and frequency levels as well as being able to smoothly transfer from grid connected to island mode.

The system consists of two back to back ENT200 three phase inverters and an isolating transformer, the isolating transformer is rated at 200 kVA. One inverter is connected to the grid and supplies power to a DC bus. The other inverter converts the DC bus power to a three phase variable frequency, variable voltage output. The power supplied by the inverter is up to **200 kW** continuous with a peak capability of 400 kW at a power factor of >0.8. A bi-directional three phase inverter is used to transfer power to and from the micro-grid. The incoming high voltage grid is transformed to a 415V distribution grid. This supplies the micro-grid with several connected loads and power sources. A by-pass breaker allows for direct connection of the LV distribution grid to the micro-grid. When the breaker is open, the inverter transfers power between the LV distribution grid and the micro-grid. In this situation it is possible to operate the micro-grid independently, with a different voltage and frequency. If the breaker is closed, and the operator wants to open it, the power flow through the inverter needs to be adjusted so that no current is flowing through any phase of the breaker. Current sensors are placed in each phase of the breaker. Both halves of the inverter operate as current source inverters. A disconnect signal would be sent to the inverter from the external local controller. Once the current in the breaker has been reduced to zero, the inverter sends a signal, causing the breaker to open. Once open, the breaker sends a signal back to the inverter, confirming it is open and the half of the inverter connected to the micro-grid will start operating as a separate, controllable 200 KW voltage source inverter. The half connected to the LV distribution grid will operate as a current source, with the current controlled by the output power measured from the voltage source section.

In order to transfer back to the grid, the operator will send a signal to the inverter. The inverter will re-synchronise with the grid frequency, and adjust the voltages to achieve a balance. This could take 10-20 seconds to achieve. Once this is achieved, the inverter will become a current source inverter again, and send a signal to the breaker requesting it to close. The breaker will send a handshake back to confirm it has closed. If not, the inverter will withdraw the close breaker request, and repeat the procedure. Once the breaker was closed, the inverter power transfer will be reduced to zero.

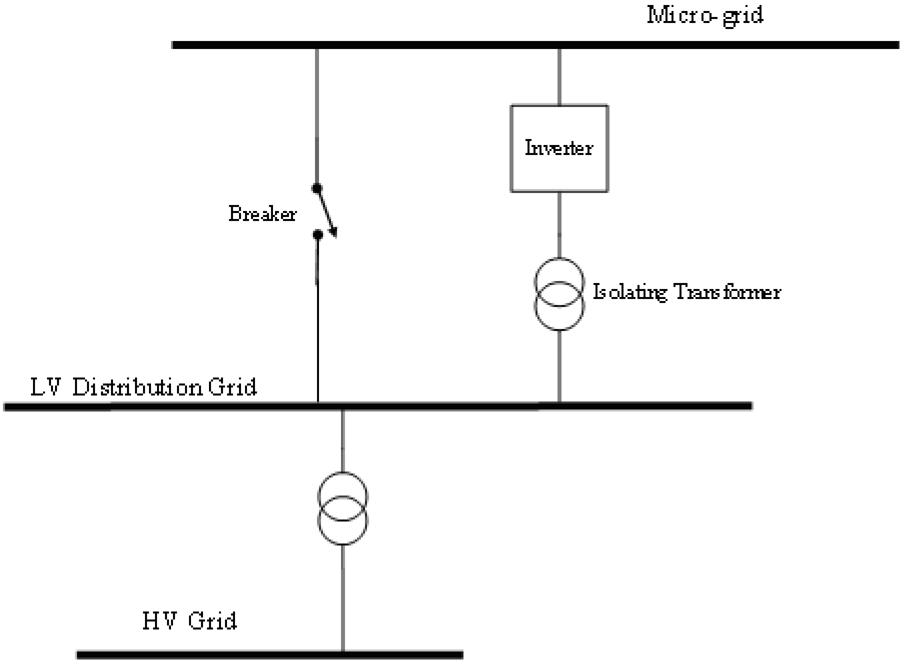


Figure 2.1 – Interconnection diagram of the I-Power inverter between main grid and microgrid.

2.1.1 *Grid characteristics*

Frequency	50 Hz ± 0.5 Hz or 60 Hz ± 0.6 Hz
Voltage (line to line)	400 V ± 10%
Power factor	>0.98

2.1.2 *Voltage output*

Frequency	45 Hz to 65 Hz in 0.01 Hz steps
Voltage (line to line)	360 V to 440 V in 1 V steps
Output current	360 A
Short circuit current	500 A
Overload shutoff	30seconds @ 400 A reducing to 5 seconds at short circuit level

2.1.3 *Inverter details*

PWM frequency	Constant frequency (4 kHz) used for both sections
DC Bus	900 V ± 100 V
ADC measurements	6 from each inverter output plus link voltage & current (Total of 14) 2 channels to be multiplexed for temperatures and board voltages

Both inverters are four limb inverters, controlled from a common TMS2704 based controller. The inverter connected to the grid is configured for three limb operation and the inverter connected to the microgrid is used as a four limb converter, with the fourth limb used to implement the neutral connection. In the inverter itself, event manager A is used for the grid linked inverter operation, while event manager B is used for the voltage source inverter mode. In this way, both halves of the inverter are synchronised and have direct access to all measurements on both sides. When starting up, the grid will charge the bus capacitor. To avoid a high inrush current, it is necessary to use a pre-charge system and this is achieved by adding an impedance in two of the lines, which is shorted out once the bus reaches a sufficiently high voltage.

The use of two back to back inverters provides no isolation between the input and the output. This is solved by adding a transformer to the grid side. Rules regarding the injection of DC current to the grid may only be satisfied if this transformer is used. If a neutral connection is required on the voltage output side of the inverter, a zig-zag transformer may be used.

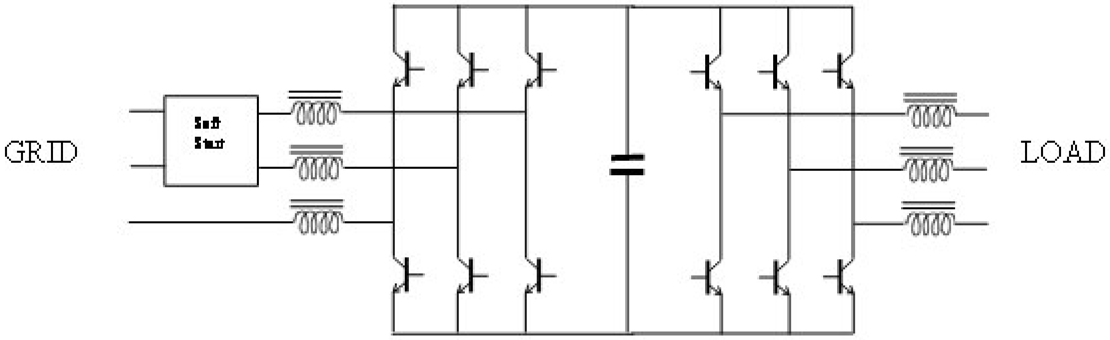


Figure 2.2 – Diagram of the back-to-back converter.

2.2 Connection information

The network diagram below shows the overall arrangement and, on the following pages, details of the connectors and connection points are shown.

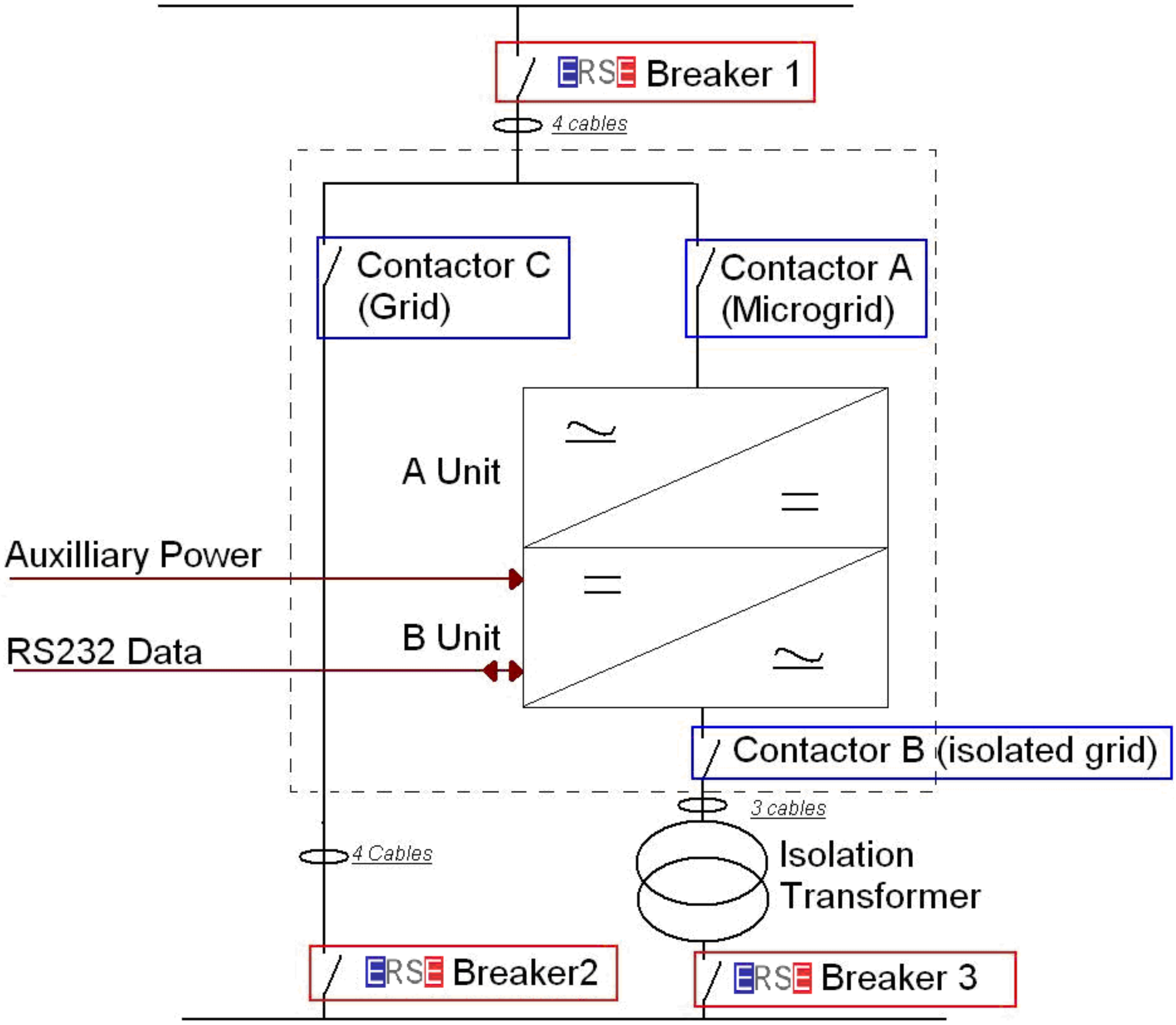


Figure 2.3 – Overall Schematic Layout.

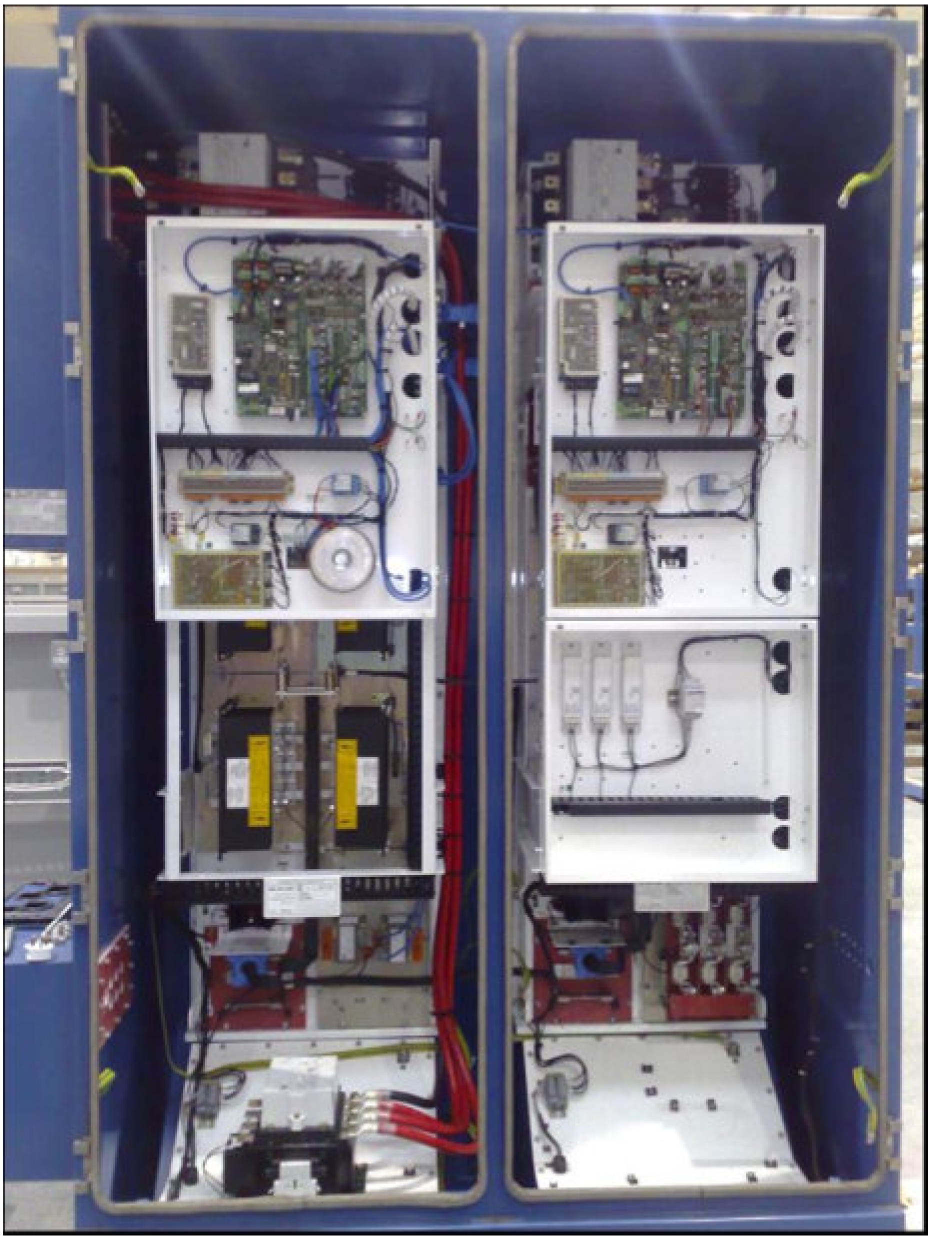
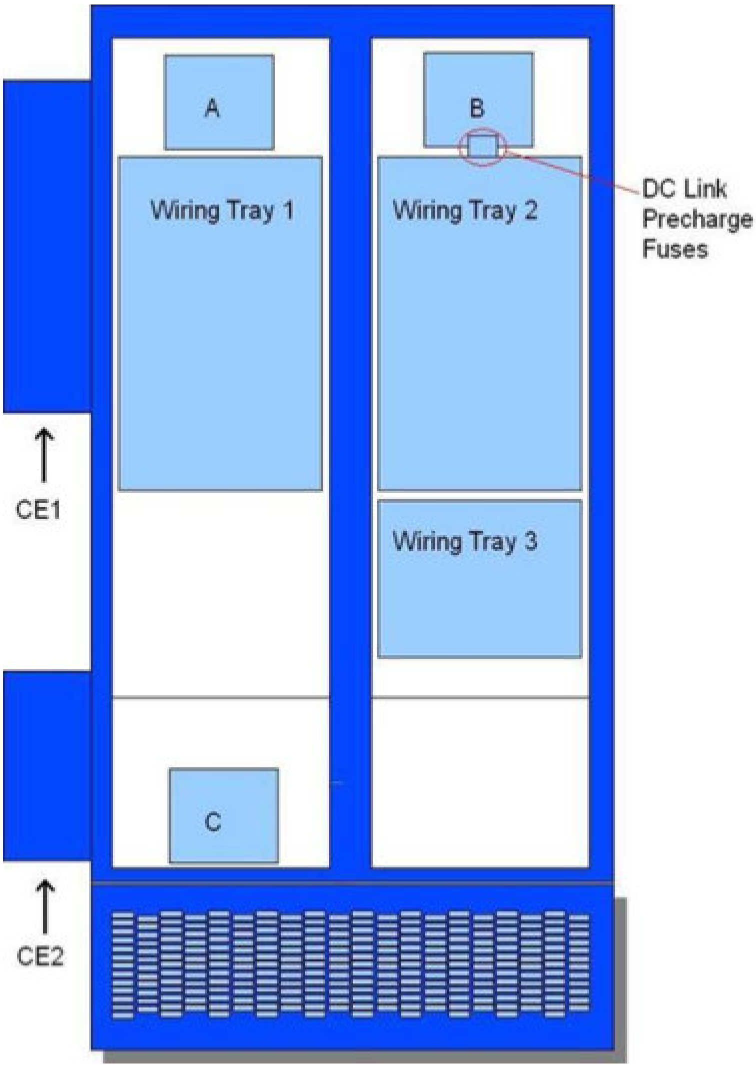


Figure 2.4 – Inside View of the I-Power ENT200 Converter



A	MicroGrid Contactor
B	Isolated Grid Contactor
C	Grid Contactor
CE1	Cable Entry point 1 For Microgrid
CE2	Cable Entry point 2 for Grid and Isolated Grid

Wiring Tray 1	(ENT400 Unit B)	contains hardware for control of the microgrid inverter
Wiring Tray 2	(ENT400 Unit A)	contains hardware for control of the Isolated grid inverter
Wiring Tray 3	(ENT400 Unit A)	contains DC link precharge hardware for both ENT units, consisting of an AC contactor and 3 ballast inductors

Figure 2.5 – Schematic representation of the I-Power ENT200 Converter

The following Figure 2.6 shows the contactor at the top of ENT400 Unit B: this is the microgrid contactor A; no wiring should be made directly to this contactor, instead use the contacts on the Schaffner EMC Filter shown on the following Figure 2.7, installing wiring through CE1

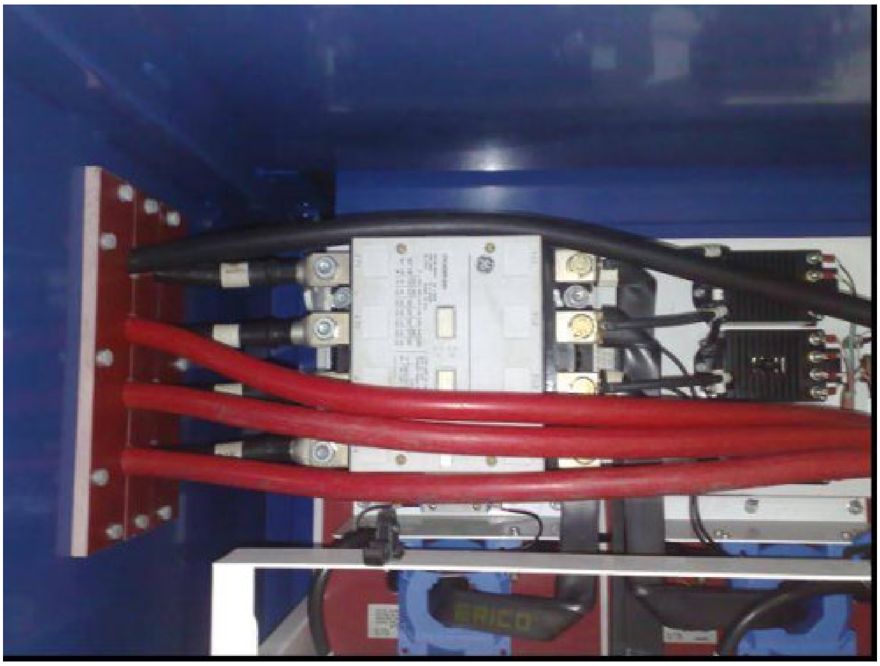


Figure 2.6 – Contactor A

Figure 2.7 – Microgrid Connection (with Schaffner filter).

The Figure 2.7 illustrates the connection points for the Microgrid, consisting of 3 phases, a neutral connection and an earth stud.

Figure 2.8 – Contactor B.

Connections for the isolated grid connection should be routed through the cabinet, entering at CE2 and terminated directly to the contactor B. Care should be taken to ensure correct wiring of the 3 phases as the DC link pre-charge system is fixed to the contactor terminals and routed through the 3 fuse holders, visible at the front of the above image.

Figure 2.9 – Contactor C (bypass breaker).

The Figure 2.9 shows the location of contactor C, which isolates the Grid connection from the Microgrid connection when not energised. Connections for the Grid should be routed through the Cable Entry box CE2 and terminated directly at this contactor. The rear connector of this contactor is the Neutral connection, with the remaining 3 connections used for 3 phase input.

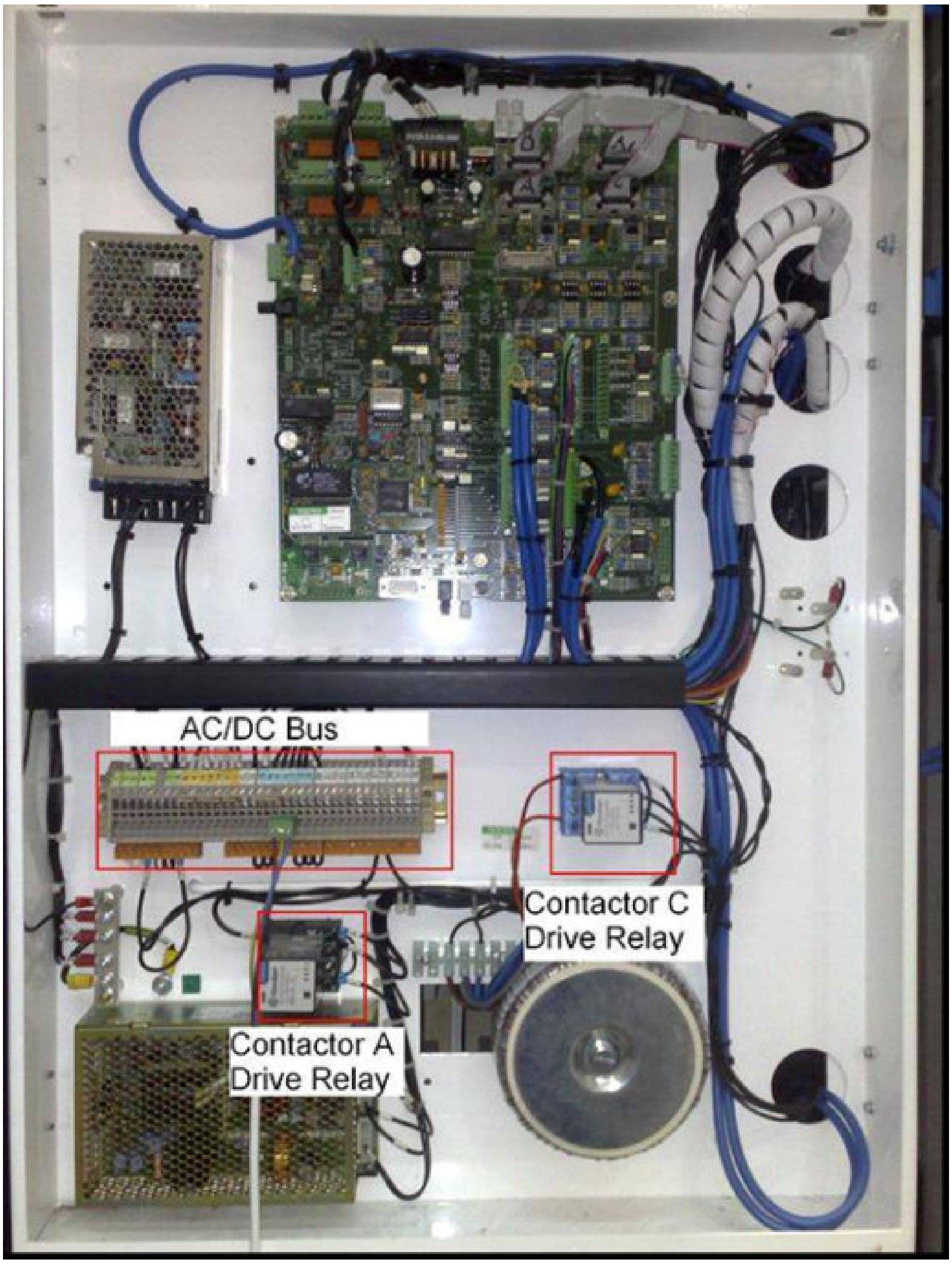


Figure 2.10 – Wiring Tray 1.

Wiring Tray 1 contains the hardware to drive inverter unit B, also contained in this tray are the drive relays for contactors A and C, as well as an AC/DC bus link. Drive Relays for contactors A and C can be tested for continuity by depressing the small blue tab to the top left of each relay; this should result in either main contactor actuating. The AC/DC bus contains main power supplies for the system, consisting of 24vdc, +/-15v and 240vac mains (also linked through to inverter unit A). Voltages are separated by coloured tabs on the rail, Green signifies 24/0 v supplies, Orange signifies +/-15 and 0 v rails, leaving Blue for 240 v mains connection.

Rail pin connections are as follows;

1 – 8	24v bus
9 – 11	+/-15v bus
13 – 20	240v Mains supply

3 TESTS PERFORMED ON ERSE MICROGRID

In general ERSE DER-TF has been used to integrate and verify results from the other work packages.

The following tests have been performed with DERs operating on a stable reference “virtual islanding” microgrid, with the interposition of the I-Power inverter between the main grid and the microgrid:

- (Chap. 3.2) voltage & frequency variation (360V÷440V, 45Hz÷65Hz)
- (Chap. 3.3) load and phase unbalance (with drop out of all or one of the phases)
- (Chap. 3.4) transfer of power TO and FROM the main grid (active and reactive)
- (Chap. 3.5) balancing of active and reactive power during this “VIRTUAL ISLANDING” (NO power flow TO and FROM main grid)

Moreover tests have been performed on the controlled transition from grid connected to “virtual islanding” operation and reverse, analyzing the instability of microgrid network during transition processes (Chap. 3.6).

3.1 Test set up and instrumentation

To analyze the behaviour of the inverter and DERs both in steady state and transient situations we decided to measure grid parameters (voltages, currents, frequency, etc.) in four different measurement point, as you can see in the Figure 3.1:

1) on the busbar 1 (LV distribution grid), before the isolation transformer
2) on the bypass breaker (only for transition tests)
3) at the output of I-Power converter, before the Schaffner filter
4) on the busbar 2 (microgrid), at the output of the filter

To obtain a complete record of all relevant information, grid parameters were also measured directly on the DERs (load, battery systems, etc) used in the tests.

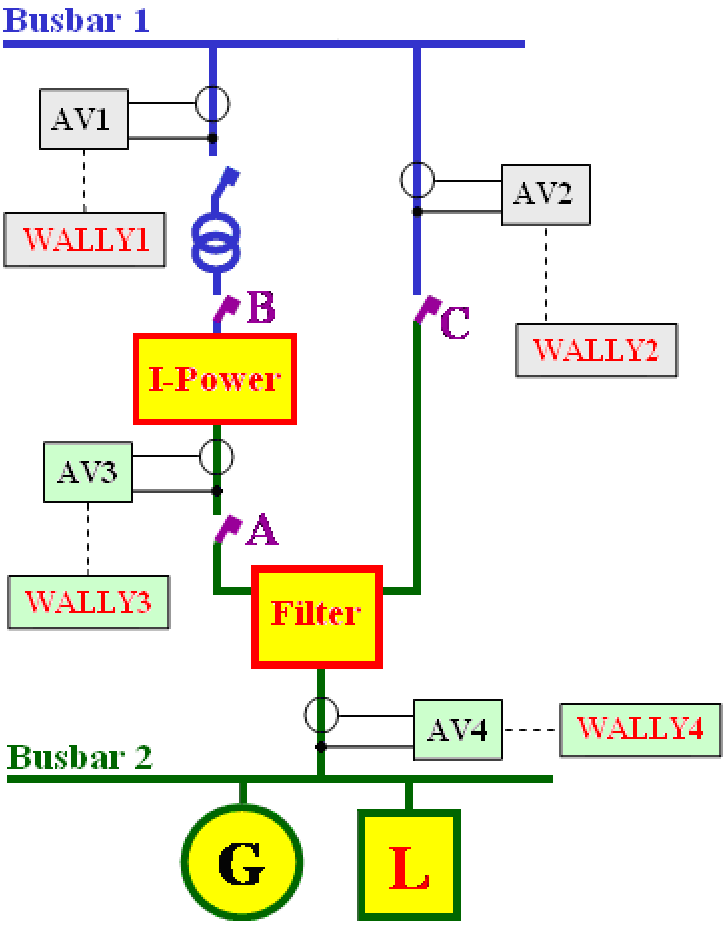


Figure 3.1 – Layout of the measurement point.

The measurement instrument selected for the purpose was the **Teamware** grid analyser **Wally**. This instrument is a highly-integrated Power Quality Analyzer compliant to the EN50160 standard [2]. It can operate in two different modes:

- in Power Meter mode it is a true RMS AC/DC wattmeter and harmonic analyzer. In this mode the instrument measures the RMS (both three-phase and single phase) values of voltages, currents, active and reactive powers, frequency, power factor, etc. and operates the harmonic analysis of the signals, measuring the THD and the DC component.
- in Transient Analyzer mode it measures, as an oscilloscope, the instantaneous values of currents and voltages, at a high sampling frequency and then calculates the spectrum of the signals, up to the 50th harmonic.

In the following figures you can see the four Wally used during the tests, operating synchronously.

Figure 3.2 – Wally 1, installed on the I-Power Electric Board

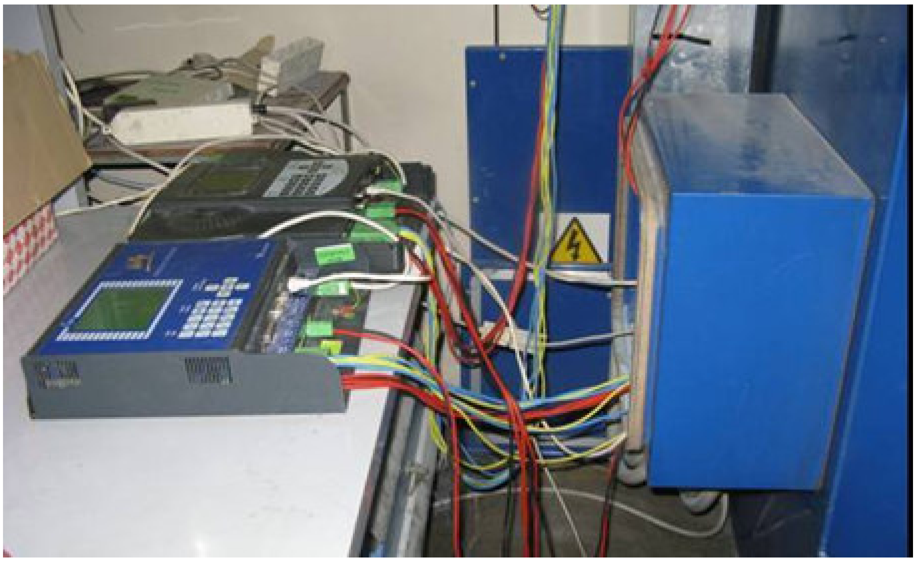


Figure 3.3 – Wally 2 and Wally 4.

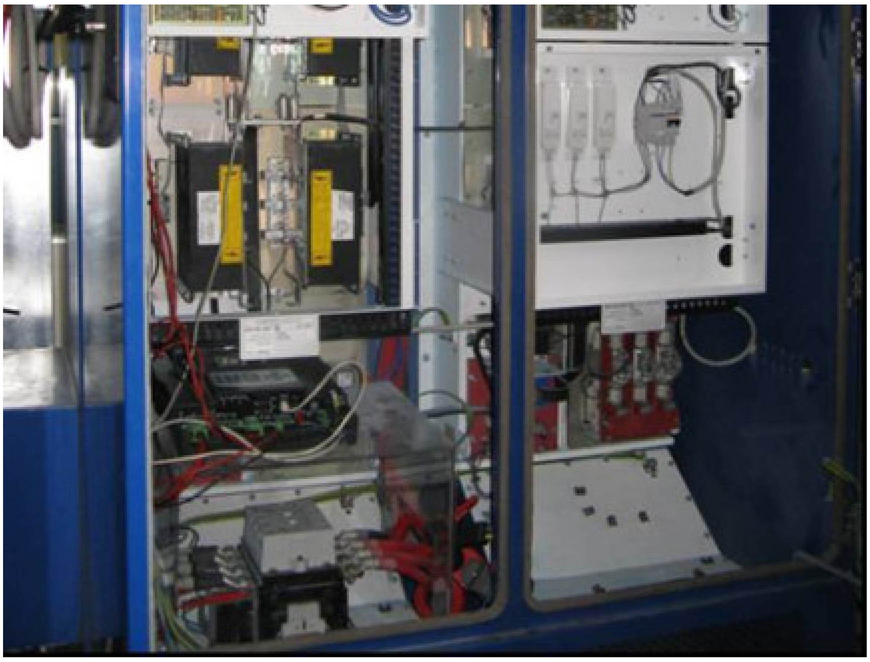


Figure 3.4 – Wally 3.

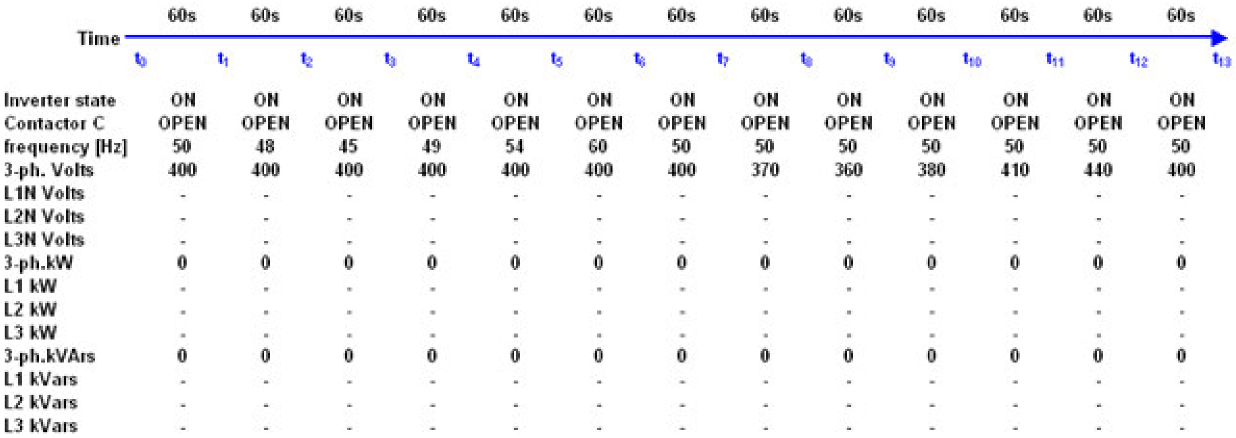
3.2 Voltage & frequency variation

The aim of these tests was to analyze both the performances of the I-Power inverter, that is able to realize and manage a stable reference microgrid characterized by values of voltage and frequency different from the main grid ones (360-440 V_{RMS} and 45-60 Hz), and the behaviour of the DERs during the grid parameters variations.

3.2.1 Test 1: Voltage & frequency variation, without load & without generation

Test setting

The measurement instruments, settled as shown in Figure 3.5, have been used in "**Power Meter**" mode configuration. The inverter supplies busbar 2, varying its voltage and frequency and different tests have been executed depending on the absence and presence of load and generation. We measured 3phase voltages, phase-to-neutral voltages, frequency, active and reactive power and currents of each phase.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz]	50	48	45	49	54	60	50	50	50	50	50	50	50
3-ph. Volts	400	400	400	400	400	400	400	370	360	380	410	440	400
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kW	0	0	0	0	0	0	0	0	0	0	0	0	0
L1 kW	-	-	-	-	-	-	-	-	-	-	-	-	-
L2 kW	-	-	-	-	-	-	-	-	-	-	-	-	-
L3 kW	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kVArs	0	0	0	0	0	0	0	0	0	0	0	0	0
L1 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-
L2 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-
L3 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 3.5 – Test 1: voltage and frequency variation, without load & without generation.

Test results

During test 1 there is no load or generation, the voltage and frequency of the microgrid are varied according to the following table.

The following charts show the RMS voltages and frequency measured on the busbar 1 and 2, at the inlet of the transformer and at the output of the inverter during the test. It was shown that the frequency and voltages values of the microgrid are totally independent from the main grid parameters and the voltage and frequency variations in microgrid don't have a significant influence on the main grid parameters.

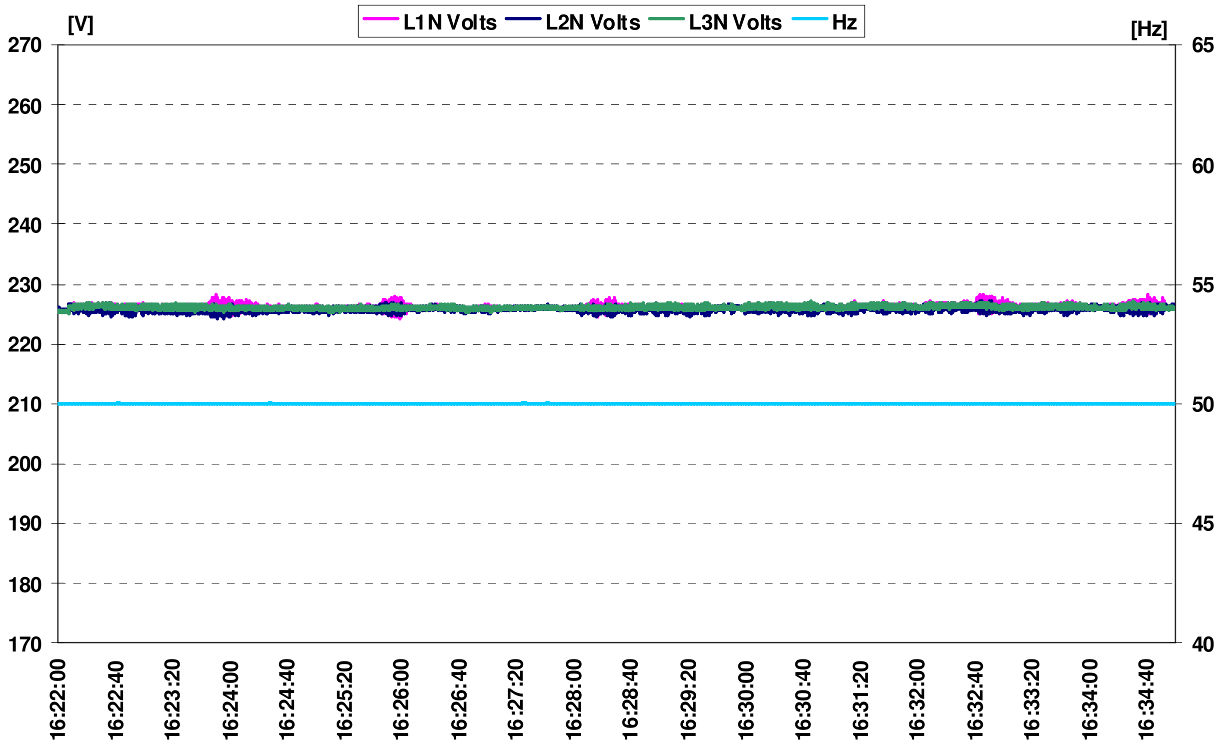


Figure 3.6 – Test 1: Phase-to-neutral voltages and frequency on busbar 1, during the Voltage&Frequency Variation (without load and generation).

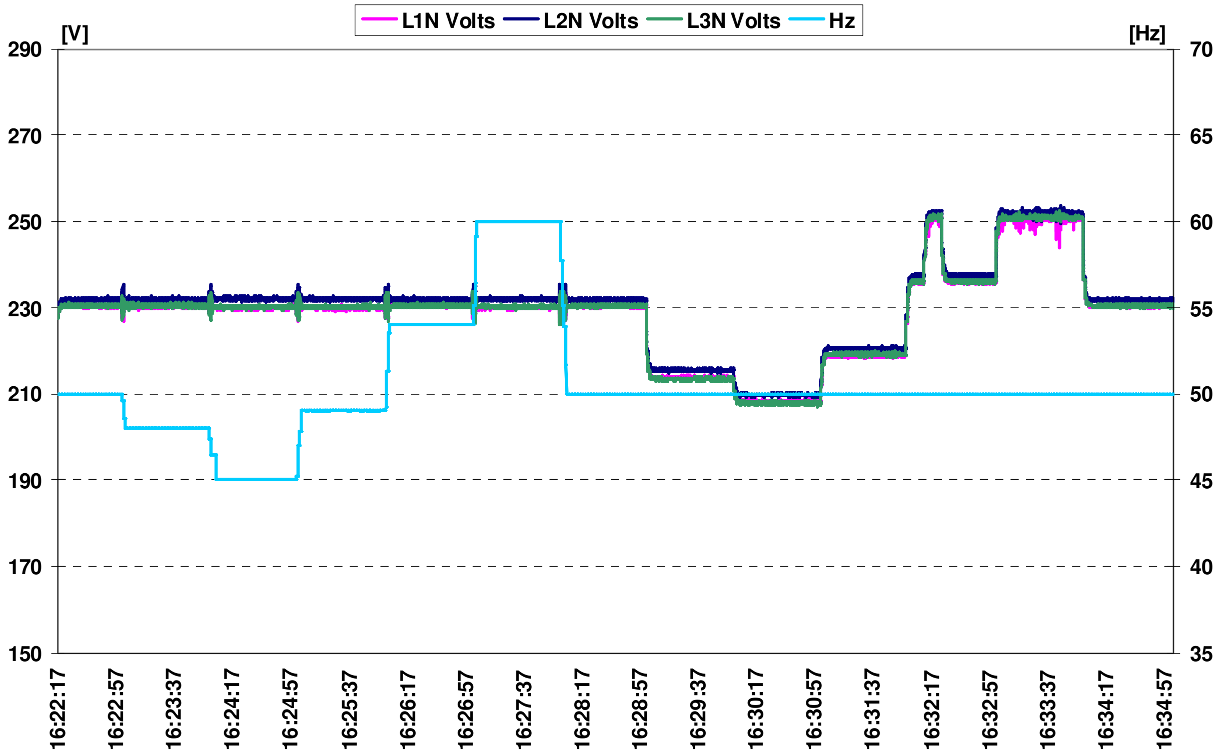


Figure 3.7 – Test 1: Phase-to-neutral voltages and frequency on busbar 2 during the Voltage&Frequency Variation (without load and generation).

The following chart shows the Total Harmonic Distortion (THD) of voltage L1 on the microgrid, measured during the test. The THD stays under the limit imposed by the EN 50160 (8%) [2]. The spikes in THD and DC component are computing errors caused by the frequency and voltage variations and have been neglected.

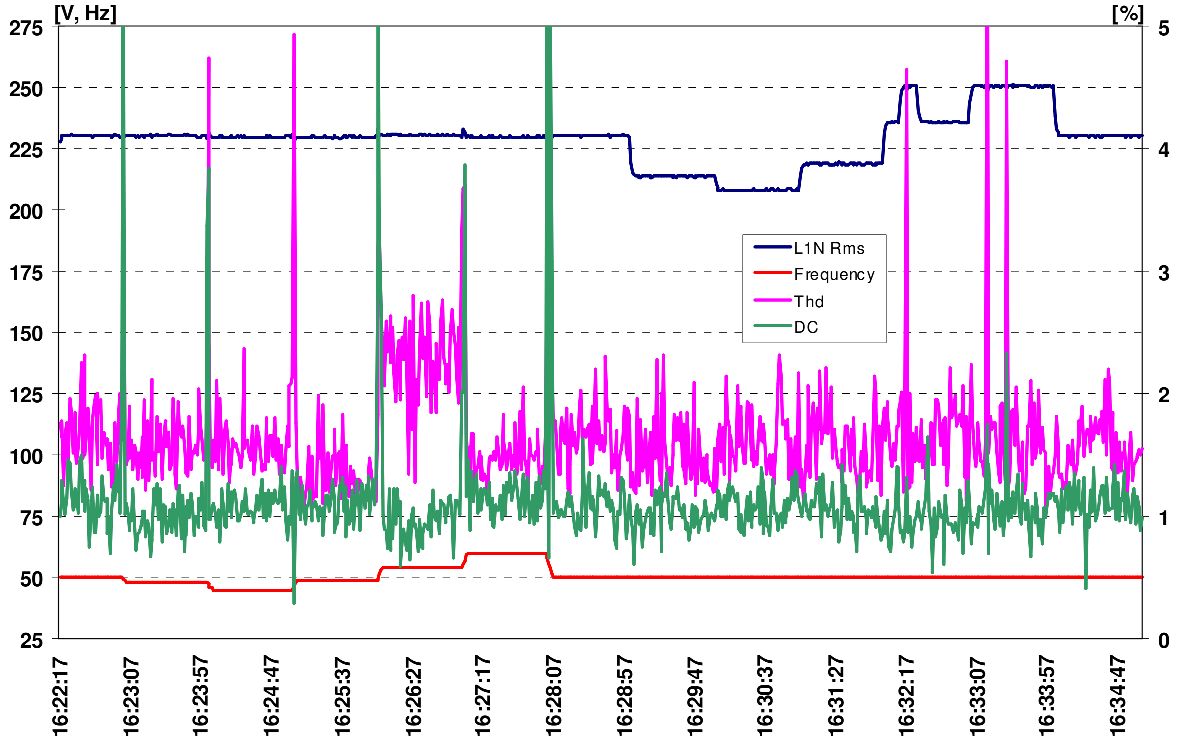
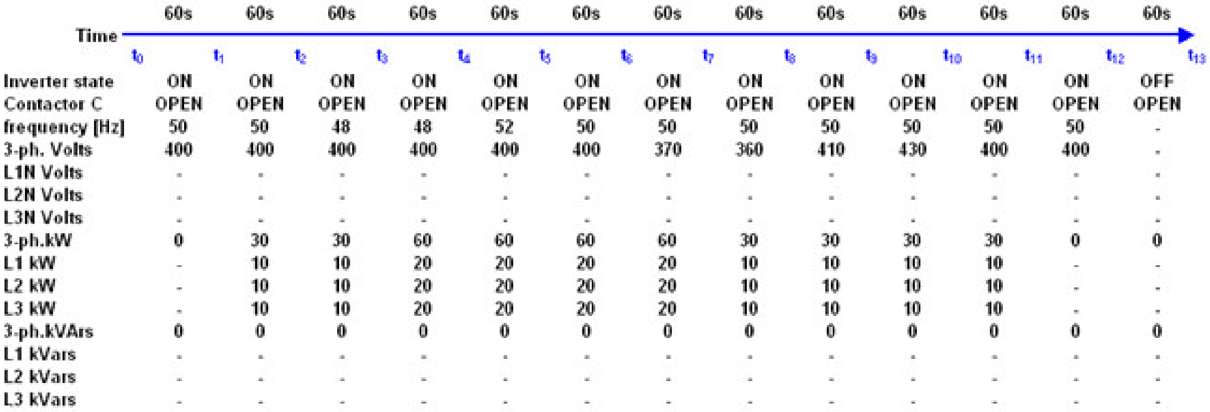


Figure 3.8 – Test 1: THD, DC component, frequency and RMS of the L1 phase voltage.

3.2.2 *Test 2: Voltage & frequency variation, with load & without generation*

Test setting

During test 2 there was only a balanced resistive load on busbar 2, voltage and frequency of the microgrid and the power requested from the load are varied according to the following table.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz]	50	50	48	48	52	50	50	50	50	50	50	50	-
3-ph. Volts	400	400	400	400	400	400	370	360	410	430	400	400	-
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kW	0	30	30	60	60	60	60	30	30	30	30	0	0
L1 kW	-	10	10	20	20	20	20	10	10	10	10	-	-
L2 kW	-	10	10	20	20	20	20	10	10	10	10	-	-
L3 kW	-	10	10	20	20	20	20	10	10	10	10	-	-
3-ph.kVArs	0	0	0	0	0	0	0	0	0	0	0	0	0
L1 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-
L2 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-
L3 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 3.9 – Test 2: voltage and frequency variation, with load & without generation

Test results

The Figure 3.10shows a correlation between the load changes in microgrid (green curve) and the three-phase voltage in main grid, due to the impedance of the connection line from I-power local board to the MV/lv transformer station (about 60 meter of length).

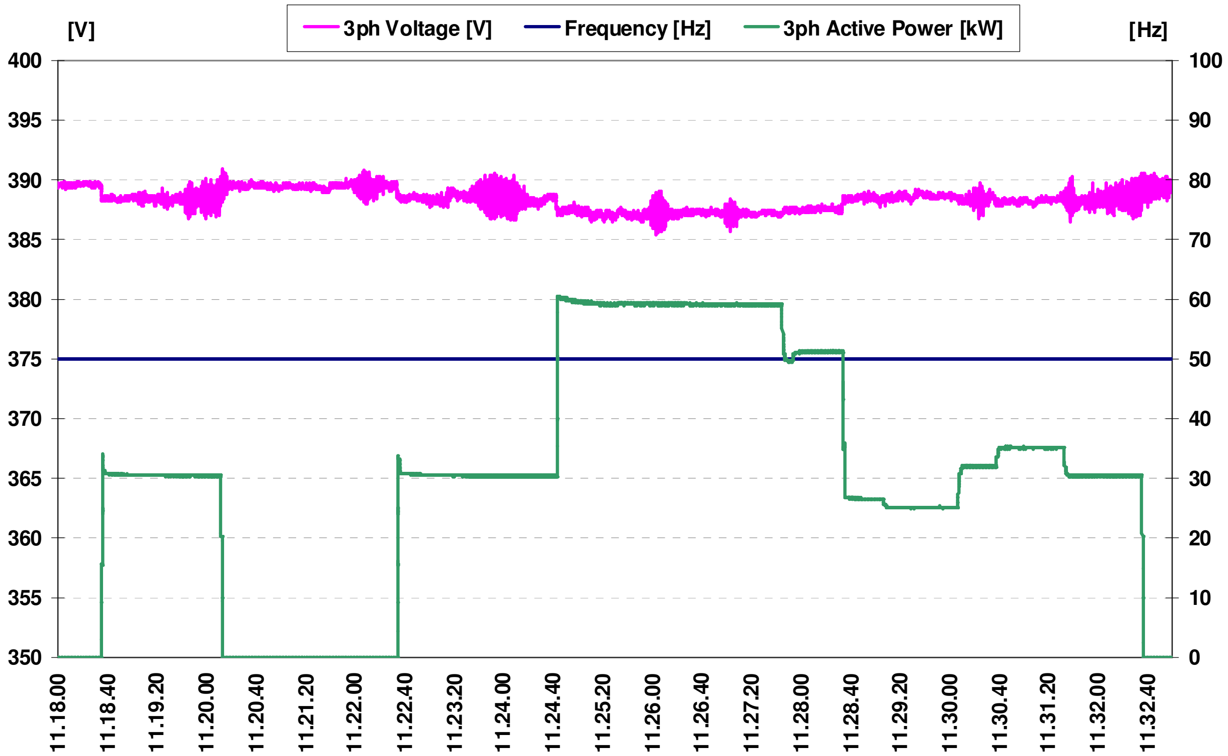


Figure 3.10 – Test 2: three-phase voltage and frequency on busbar 1 during the Voltage&Frequency Variation (with a variable balanced resistive load)

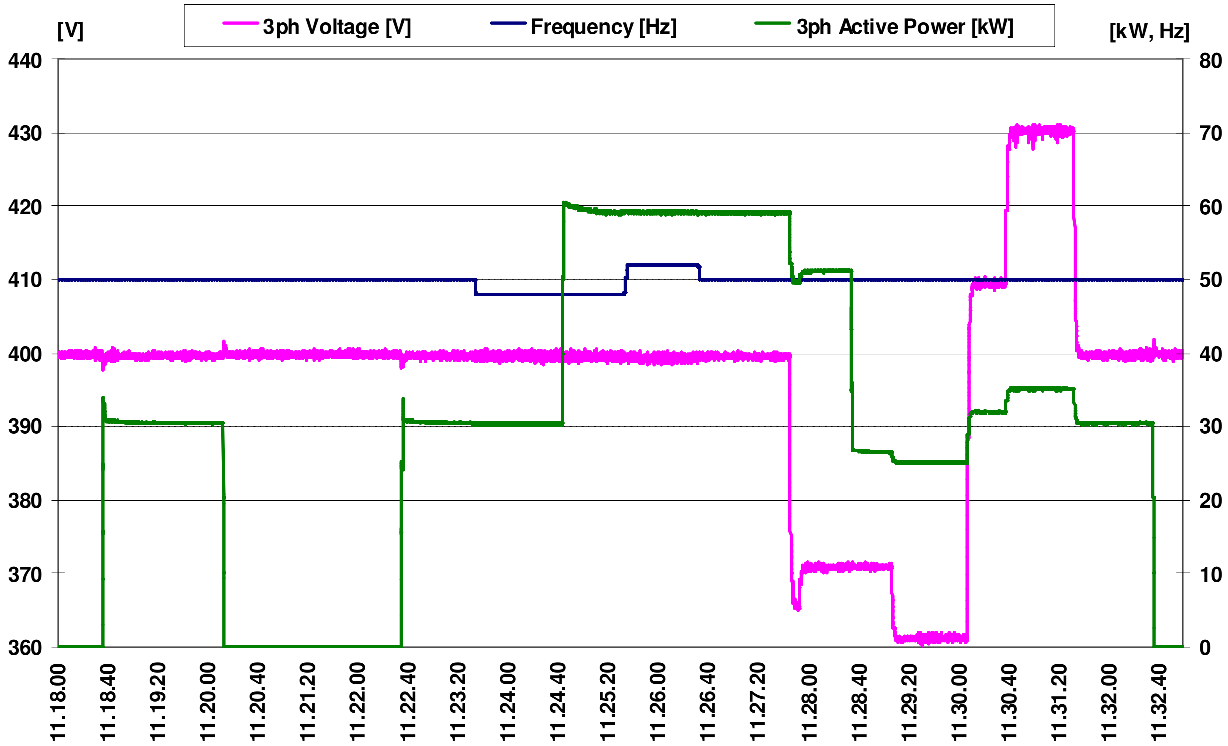


Figure 3.11 – Test 2: three-phase voltages and frequency on busbar 2 during the Voltage&Frequency Variation (with a variable balanced resistive load).

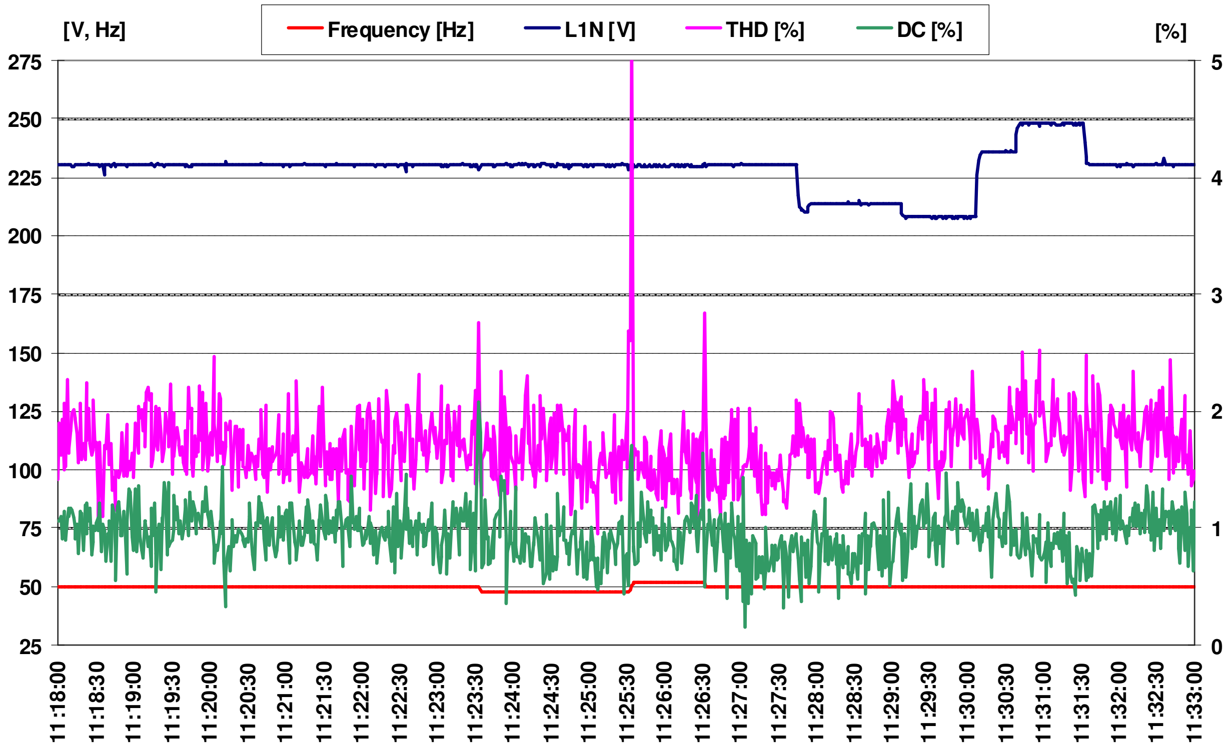
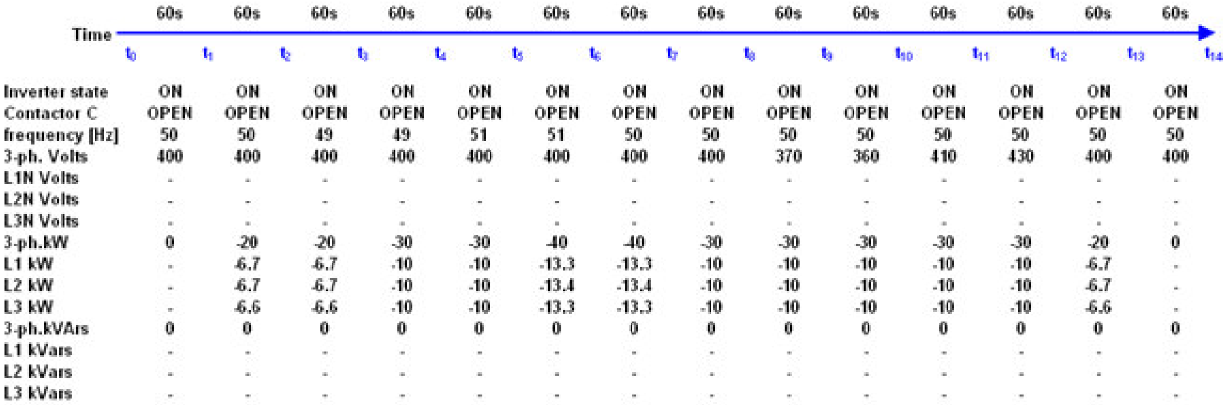


Figure 3.12 – Test 2: THD, DC component, frequency and RMS of the L1 phase voltage.

3.2.3 Test 3: Voltage & frequency variation, with load & with generation

Test setting

During test 3 there was a generator on busbar 2, voltage and frequency of the microgrid and the power supplied from the generator were then varied according to the following table.
The generator is a 100 kVA inverter with ZEBRA™ energy storage system.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz]	50	50	49	49	51	51	50	50	50	50	50	50	50	50
3-ph. Volts	400	400	400	400	400	400	400	400	370	360	410	430	400	400
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kW	0	-20	-20	-30	-30	-40	-40	-30	-30	-30	-30	-30	-20	0
L1 kW	-	-6.7	-6.7	-10	-10	-13.3	-13.3	-10	-10	-10	-10	-10	-6.7	-
L2 kW	-	-6.7	-6.7	-10	-10	-13.4	-13.4	-10	-10	-10	-10	-10	-6.7	-
L3 kW	-	-6.6	-6.6	-10	-10	-13.3	-13.3	-10	-10	-10	-10	-10	-6.6	-
3-ph.kVArs	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L1 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L2 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L3 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 3.13 – Test 3: voltage and frequency variation, with load & with generation

Test results

The following graph shows the 3phase voltage, active power and frequency measured on busbar 1, at the primary of the transformer.

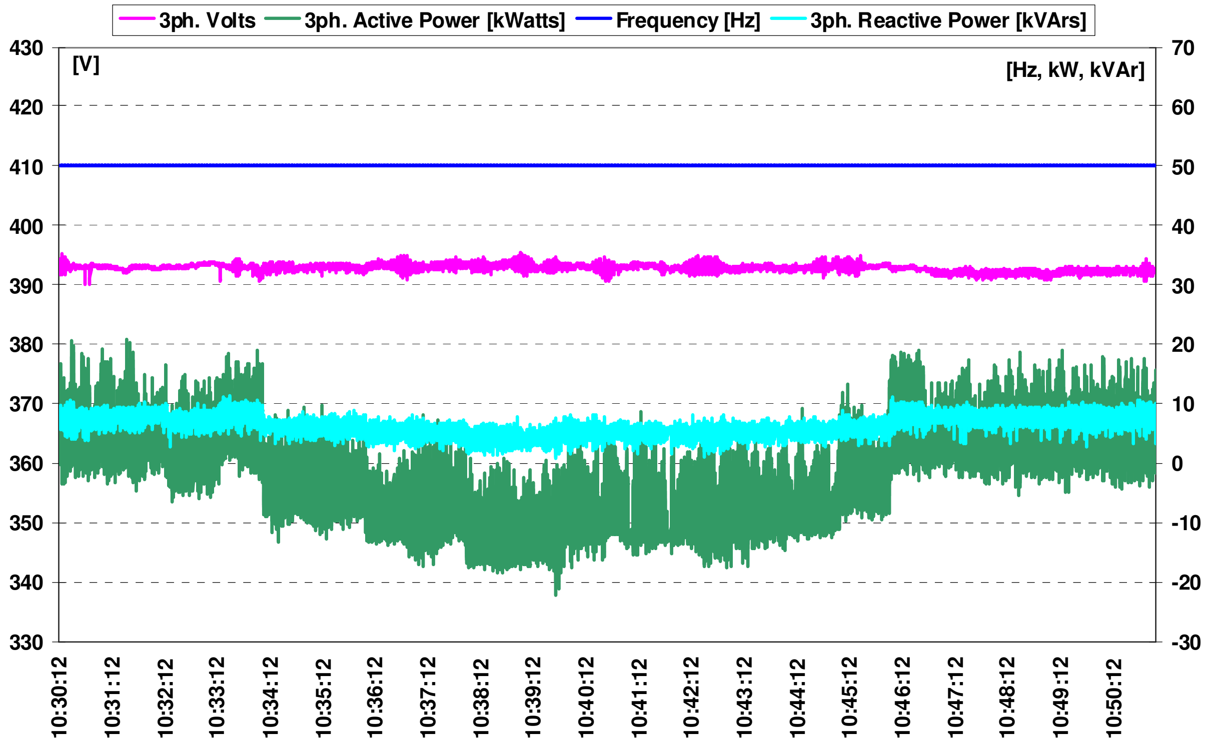


Figure 3.14 – Test 3: three phase voltage, frequency, active and reactive power measured on busbar 1, during the voltage and frequency variation.

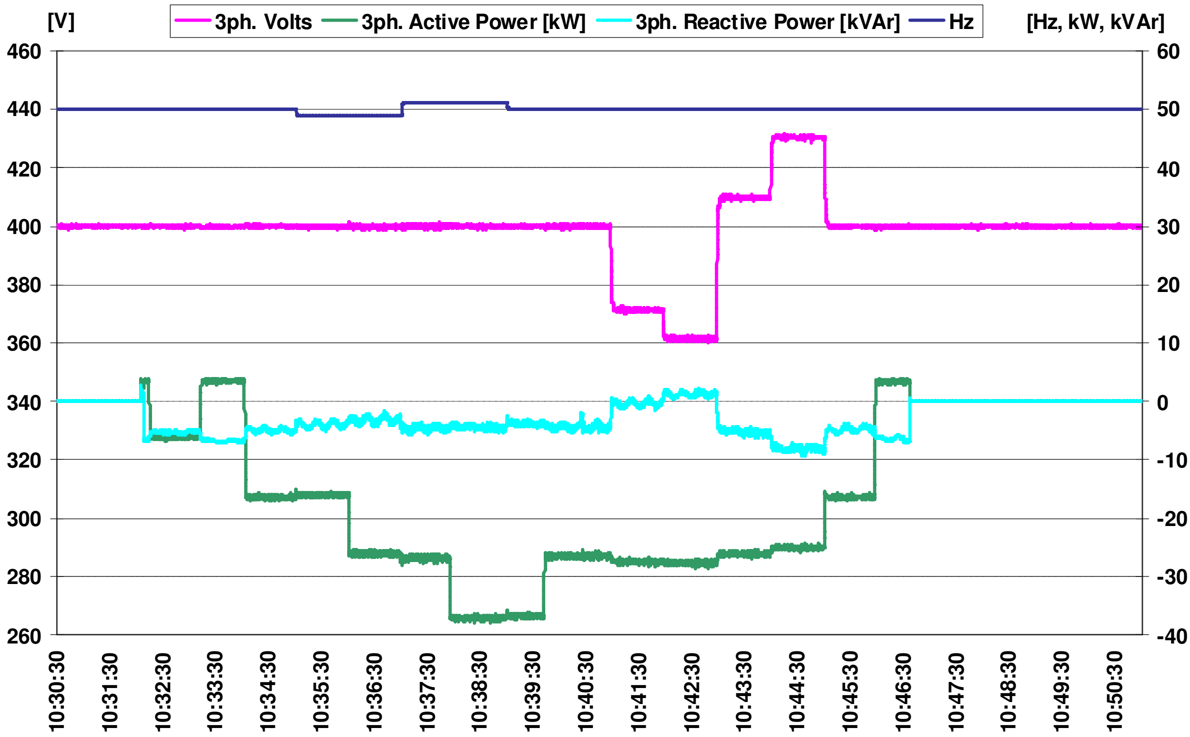


Figure 3.15 – Test 3: three phase voltage, frequency, active and reactive power measured on busbar 2, during the voltage and frequency variation.

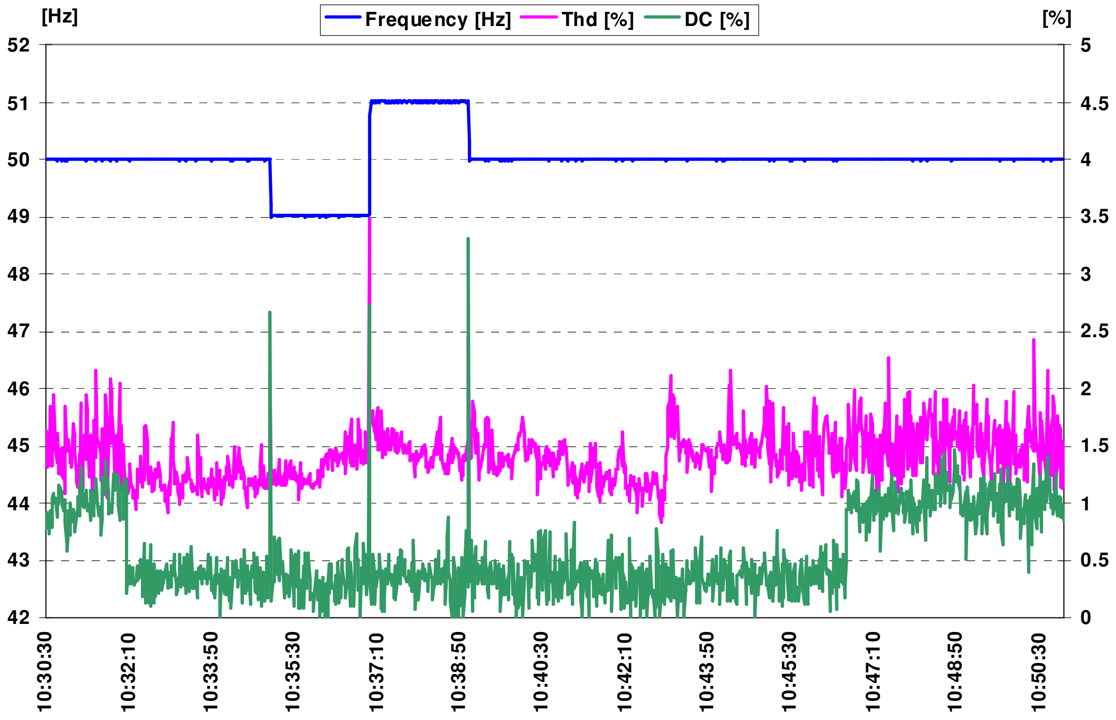


Figure 3.16 – Test 3: THD, DC component, frequency of the L1 phase voltage.

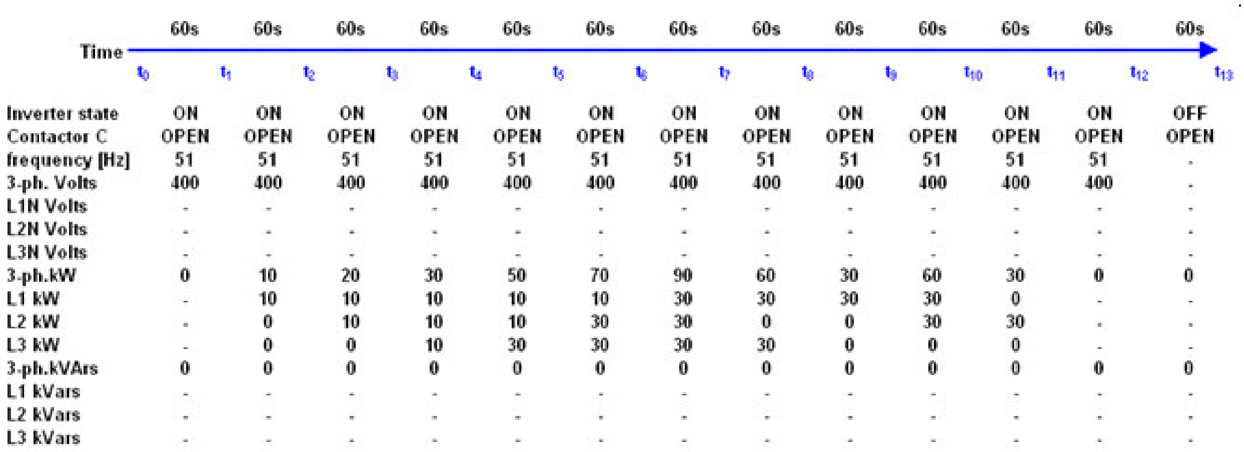
3.3 Load&Phase unbalance

The aim of this test was to analyze the I-Power inverter performance in the presence of an unbalanced load or generation on the microgrid (busbar 2) and to verify its ability to show a balanced load versus the main grid (busbar 1).

3.3.1 Test 1: Load&Phase unbalance, with resistive load & without generation

Test setting

The measurement instruments, set up as shown in Figure 3.17, were used in PowerMeter mode configuration. The inverter supplies busbar 2 with a stable voltage of 400 V_{RMS} and a frequency of 51 Hz, with an unbalanced load or generation. We measured 3phase voltages, phase-to-neutral voltages, frequency, active and reactive power and currents of each phase.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz]	51	51	51	51	51	51	51	51	51	51	51	51	-
3-ph. Volts	400	400	400	400	400	400	400	400	400	400	400	400	-
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kW	0	10	20	30	50	70	90	60	30	60	30	0	0
L1 kW	-	10	10	10	10	10	30	30	30	30	0	-	-
L2 kW	-	0	10	10	10	30	30	0	0	30	30	-	-
L3 kW	-	0	0	10	30	30	30	30	0	0	0	-	-
3-ph.kVArs	0	0	0	0	0	0	0	0	0	0	0	0	0
L1 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-
L2 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-
L3 kVars	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 3.17 – Test 1: Load&Phase unbalance, with resistive-Load & without Generators

Test results

The Figure 3.19 shows the voltage and active power for each phase during the test of unbalance. You can see that the maximum voltage unbalance during the test is 1,3% but generally the voltage unbalance is under 1%.

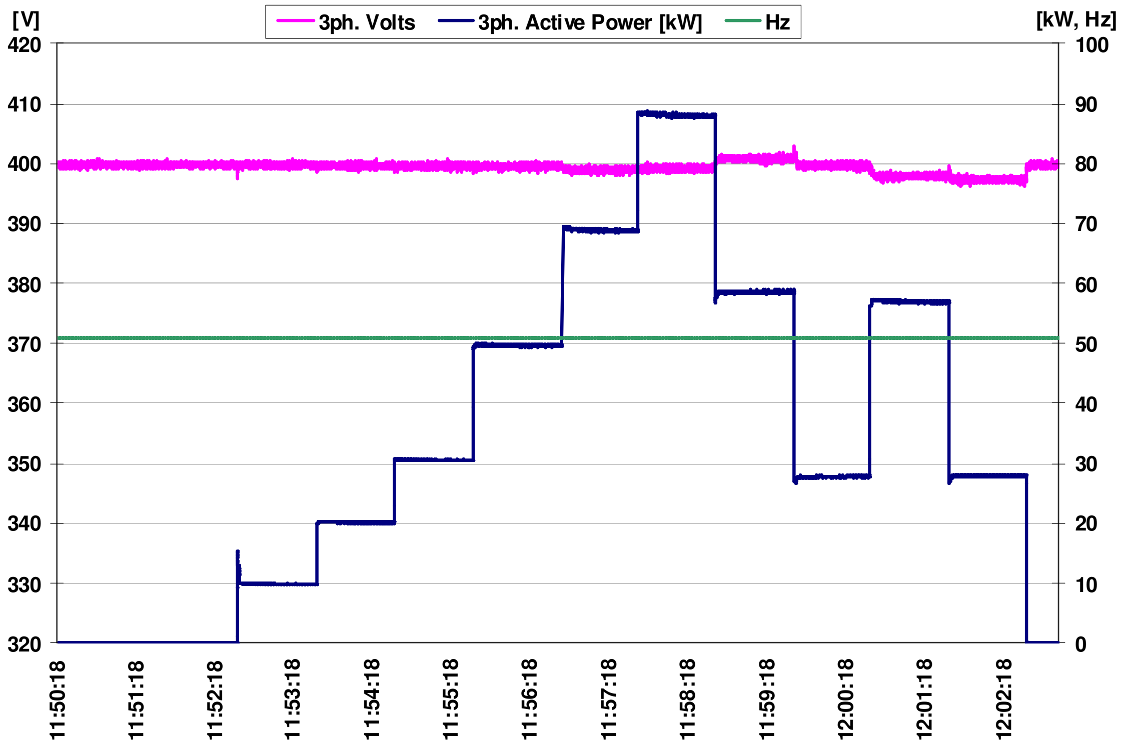


Figure 3.18 – Test 1: three-phase voltage, frequency and active power measured on busbar 2 during the load&phase unbalance, with a resistive load.

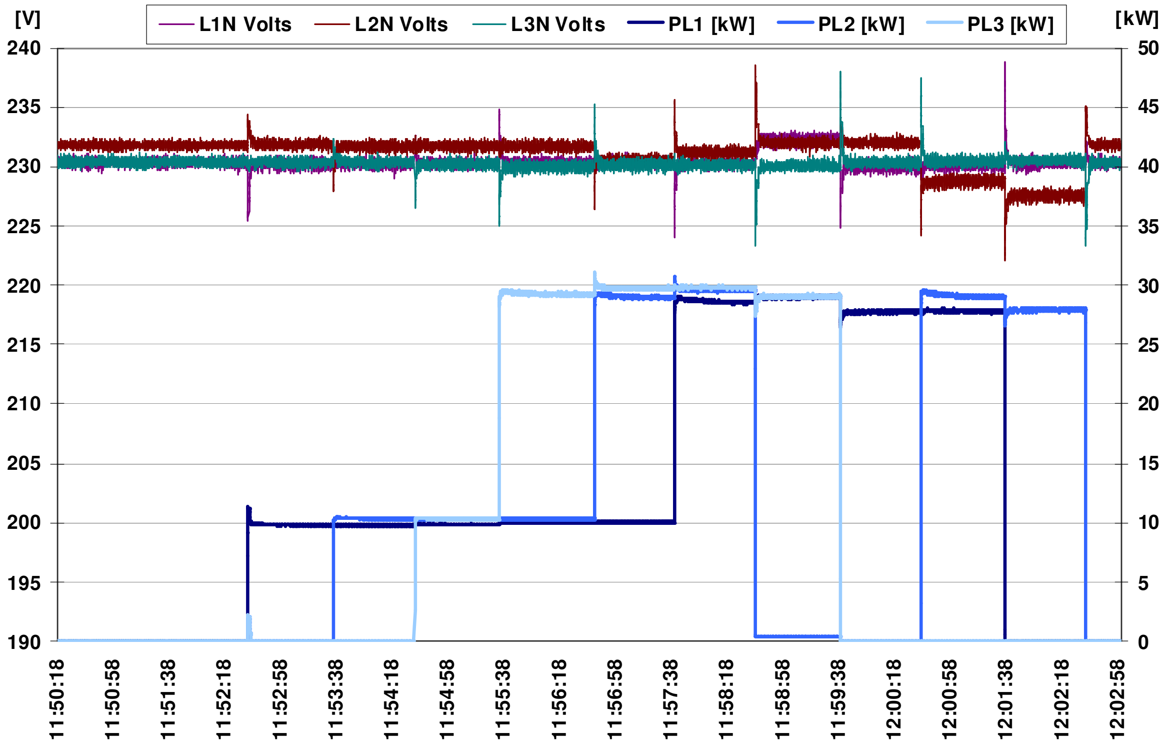


Figure 3.19 – Test 1: phase-to-neutral voltage and active power for each phase measured on busbar 2 during the load&phase unbalance, with a resistive load.

As shown in Figure 3.20 the main grid has a balanced load even if the microgrid load is unbalanced and additionally there is no voltage unbalance.

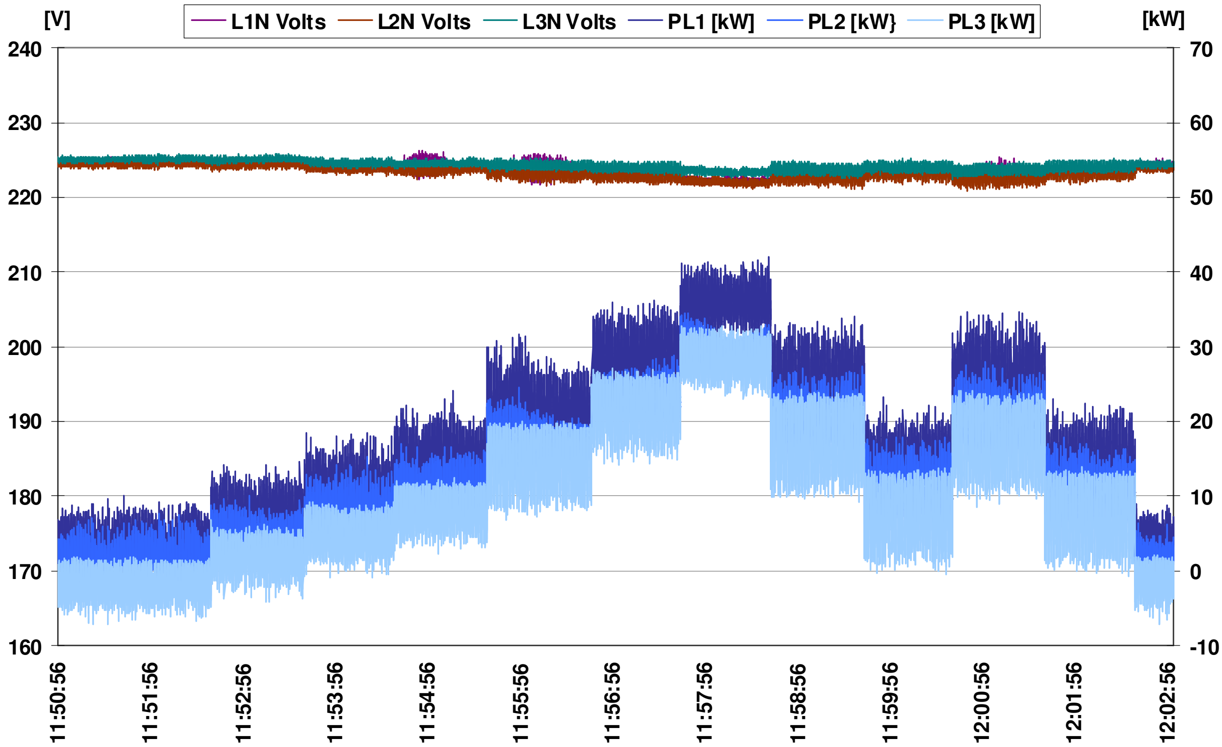
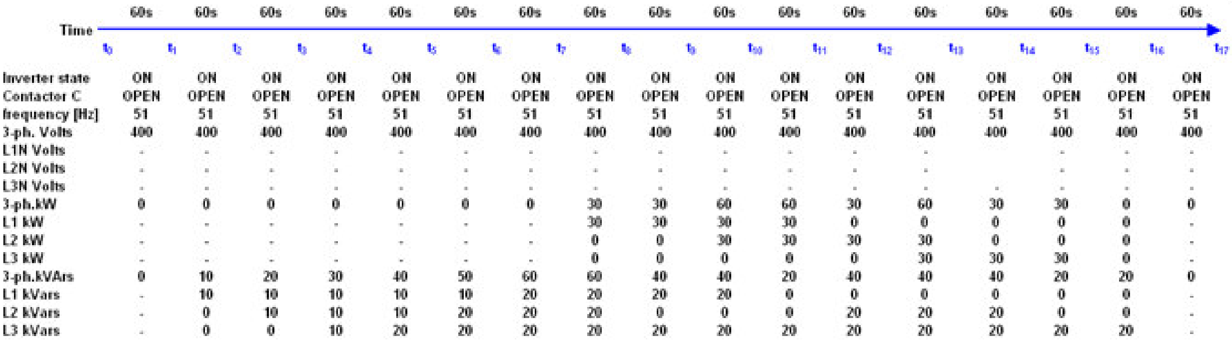


Figure 3.20 – Test 1: phase-to-neutral voltage and active power for each phase measured on busbar 1 during the load&phase unbalance, with a resistive load.

3.3.2 Test 2: Load&Phase unbalance, with resistive/inductive-Load & without Generation

Test setting

The measurement instruments, set up as shown in Figure 3.21, were used in PowerMeter mode configuration.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz]	51	51	51	51	51	51	51	51	51	51	51	51	51	51	51	51	51
3-ph. Volts	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kW	0	0	0	0	0	0	0	30	30	60	60	30	60	30	30	0	0
L1 kW	-	-	-	-	-	-	-	30	30	30	30	0	0	0	0	0	-
L2 kW	-	-	-	-	-	-	-	0	0	30	30	30	30	0	0	0	-
L3 kW	-	-	-	-	-	-	-	0	0	0	0	0	30	30	30	0	-
3-ph.kVArs	0	10	20	30	40	50	60	60	40	40	20	40	40	40	20	20	0
L1 kVars	-	10	10	10	10	10	20	20	20	20	0	0	0	0	0	0	-
L2 kVars	-	0	10	10	10	20	20	20	0	0	0	20	20	20	0	0	-
L3 kVars	-	0	0	10	20	20	20	20	20	20	20	20	20	20	20	20	-

Figure 3.21 – Test 2: Load&Phase unbalance, with resistive/inductive Load & without Generators

Test results

As in the test 1, the maximum voltage unbalance shown in the Figure 3.23 is 1,3%, (only during a phase of the test); generally the value is under 1% (about 0,8%).

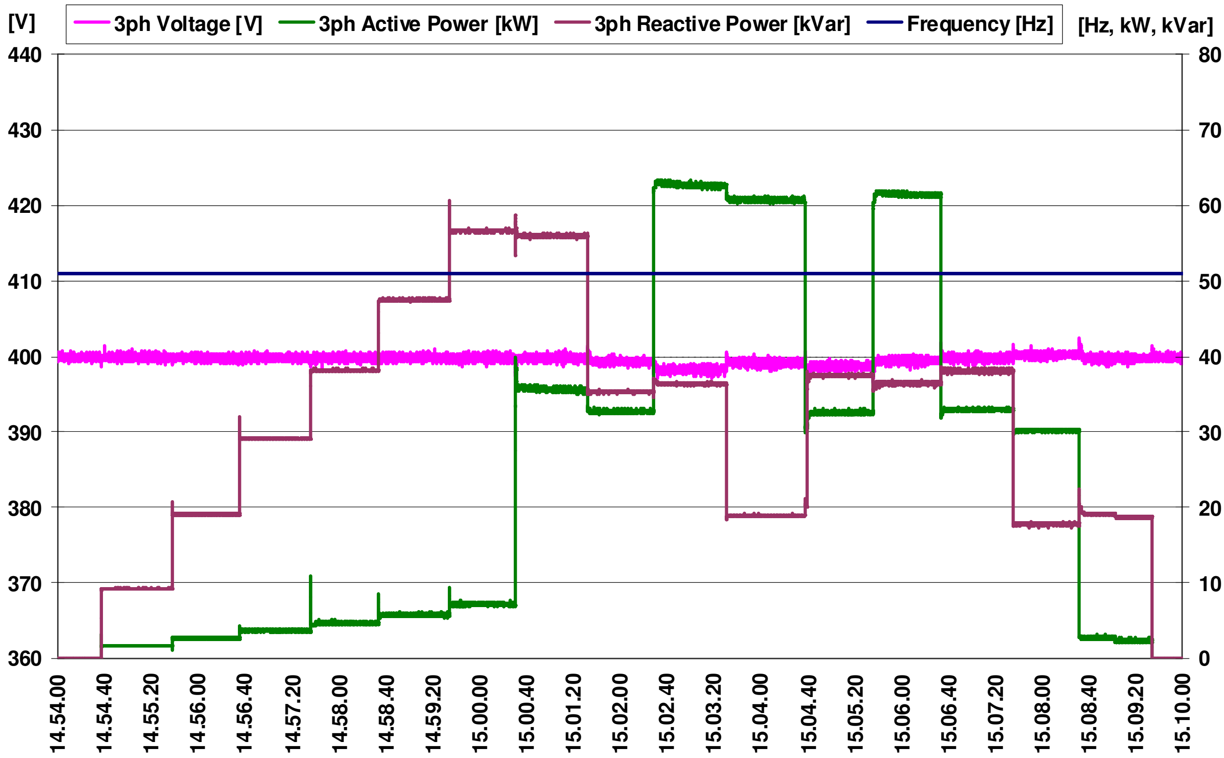


Figure 3.22 – Test 2: three-phase voltage, frequency, active and reactive power measured on busbar 2 during the load&phase unbalance, with a resistive and inductive load.

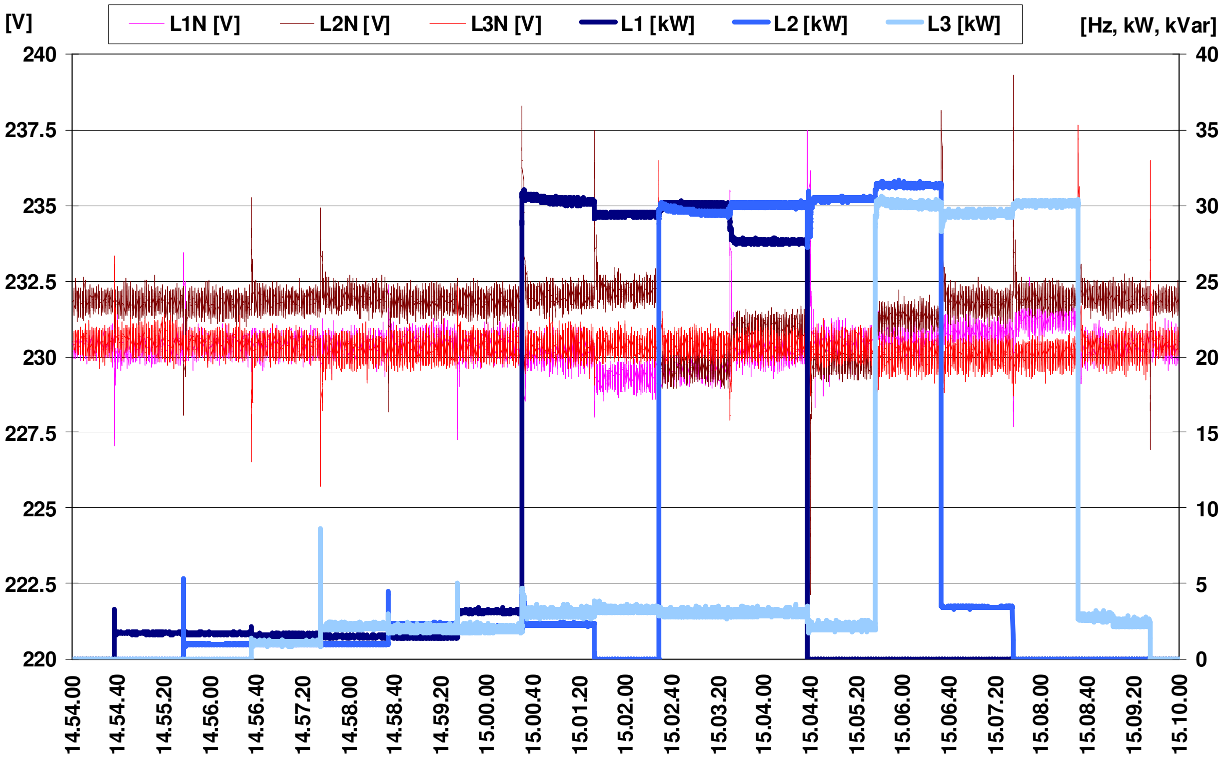


Figure 3.23 – Test 2: phase-to-neutral voltage and active power for each phase measured on busbar 2 during the load&phase unbalance, with a resistive and inductive load.

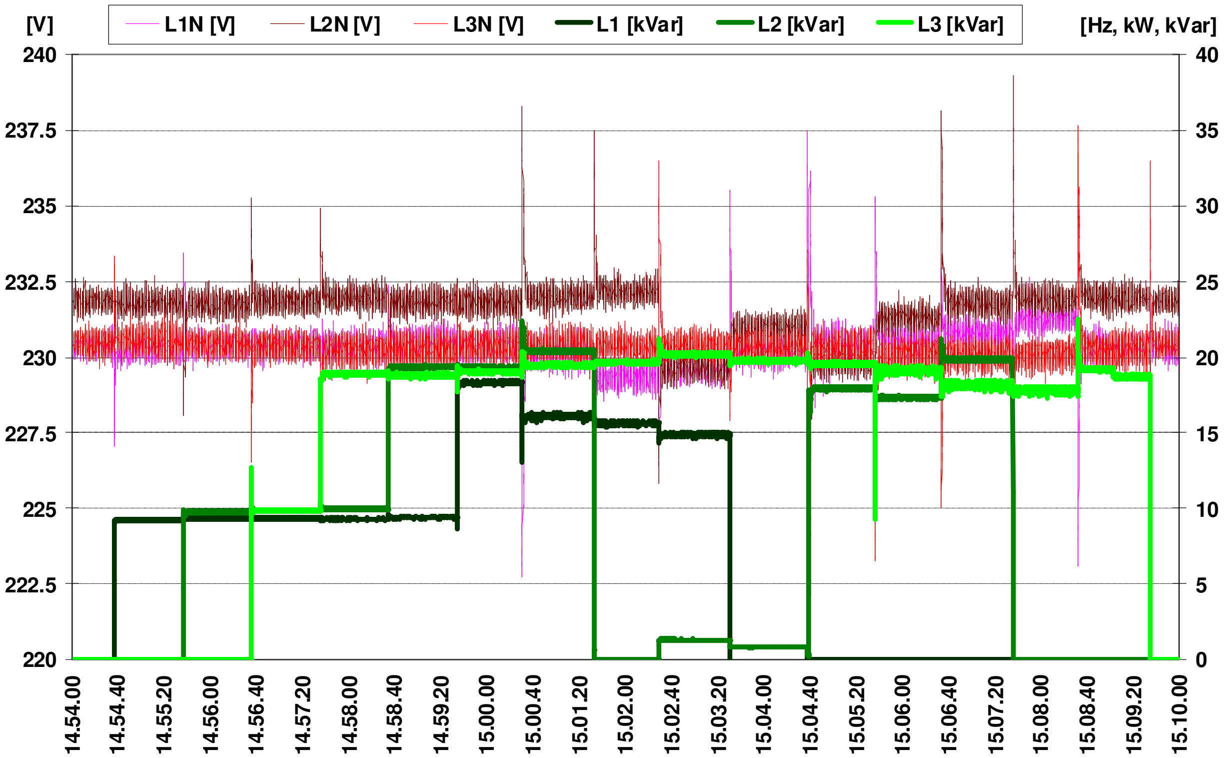


Figure 3.24 – Test 2: phase-to-neutral voltage and reactive power for each phase measured on busbar 2 during the load&phase unbalance, with a resistive and inductive load.

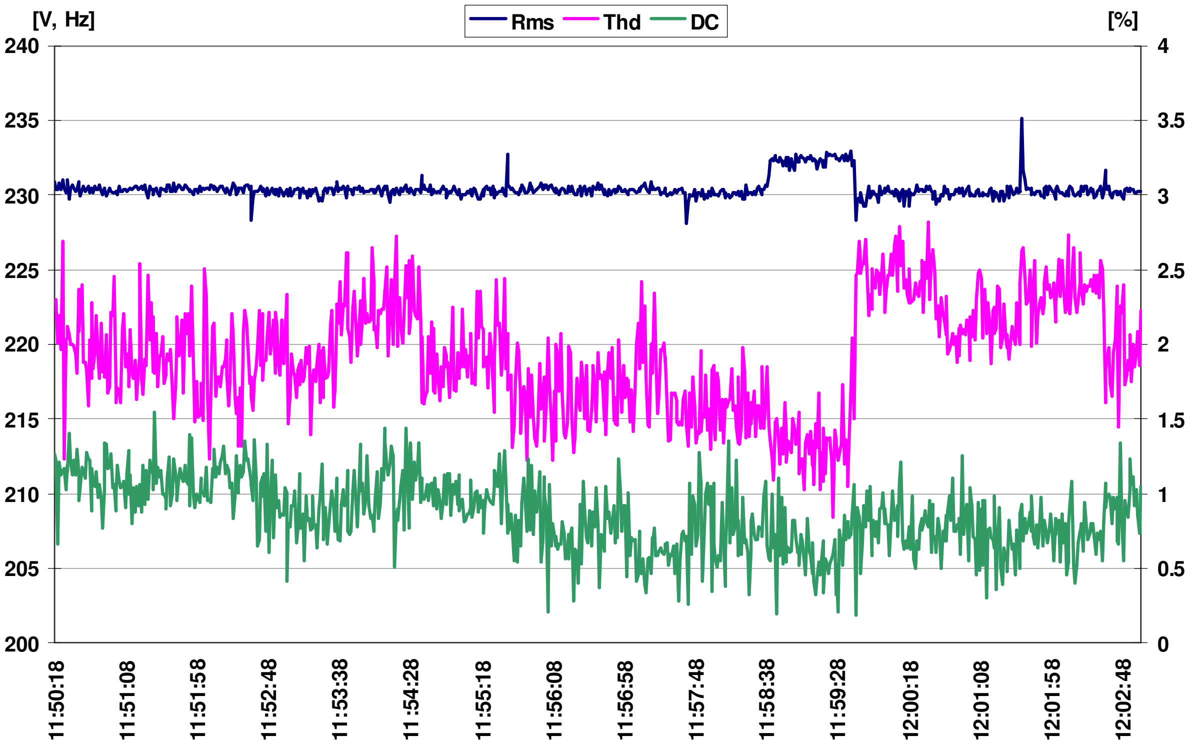


Figure 3.25 – Test 2: THD, DC component and RMS value of L1 phase voltage on busbar 2.

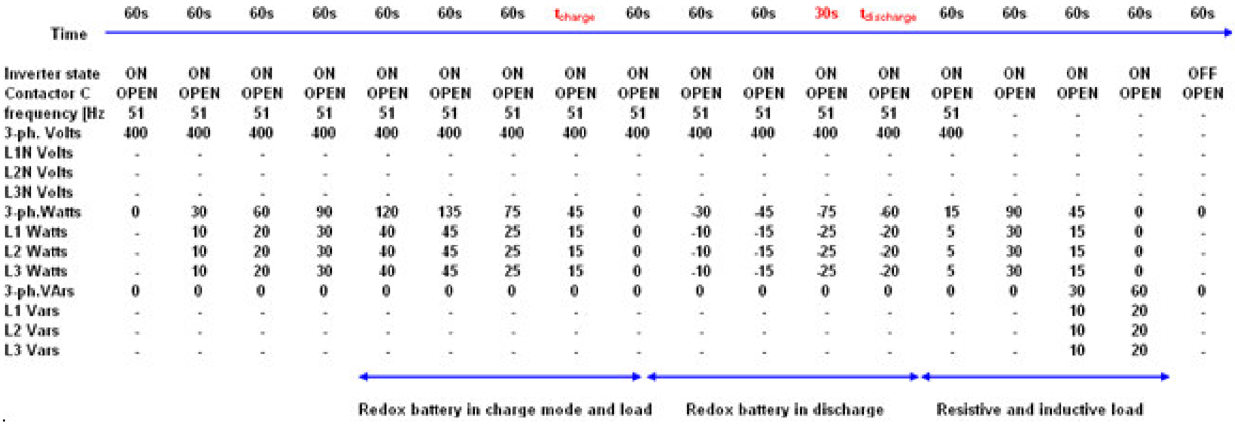
3.4 Transfer of power TO and FROM the main grid

During this test the I-power supplies the programmable load and the Redox battery storage system, both connected on the busbar 2, and can take generated power from the Redox battery storage system.
The aim of this test was to analyze the I-power inverter performance in presence of a high load on the busbar 2 and its ability to manage the inversion of the transfer of active and reactive power between the microgrid and the main grid.

3.4.1 Test 1: Transfer of power TO and FROM the main grid (active and reactive)

Test setting

The 3-phase voltages and currents are measured at the secondary of the converter, at the primary of transformer and at the output of the Redox battery converter, with 3 synchronized acquisition instruments (Teamware – WALLY). The test set up is shown in Figure 3.26.



Time	60s	60s	60s	60s	60s	60s	60s	t_{charge}	60s	60s	60s	30s	$t_{discharge}$	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz	51	51	51	51	51	51	51	51	51	51	51	51	51	51	-	-	-	-
3-ph. Volts	400	400	400	400	400	400	400	400	400	400	400	400	400	400	-	-	-	-
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.Watts	0	30	60	90	120	135	75	45	0	-30	-45	-75	-60	15	90	45	0	0
L1 Watts	-	10	20	30	40	45	25	15	0	-10	-15	-25	-20	5	30	15	0	-
L2 Watts	-	10	20	30	40	45	25	15	0	-10	-15	-25	-20	5	30	15	0	-
L3 Watts	-	10	20	30	40	45	25	15	0	-10	-15	-25	-20	5	30	15	0	-
3-ph.VArs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	60	0
L1 Vars	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	20	-
L2 Vars	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	20	-
L3 Vars	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	20	-

Figure 3.26 – Test 1: Transfer of power TO and FROM the main grid (active and reactive).

Test results

During the test there is an interval of time in which the THD exceeds the threshold of 8% (see Figure 3.29) and the voltage on the network is distorted. As it is shown in the Figure 3.28, the problem starts when the Redox battery storage system starts the charge operation and it falls when the resistive load decreases.
The disturb does not seem to be caused by the simultaneous operation of the I-Power inverter and the Redox battery inverter, because it falls during a reduction of the resistive load set-up and with the two inverters still in operation.
Possible causes could be the high load supplied by the inverter or the impedance of the inverter network in this specific test configuration, which is modified with the resistive load variation.

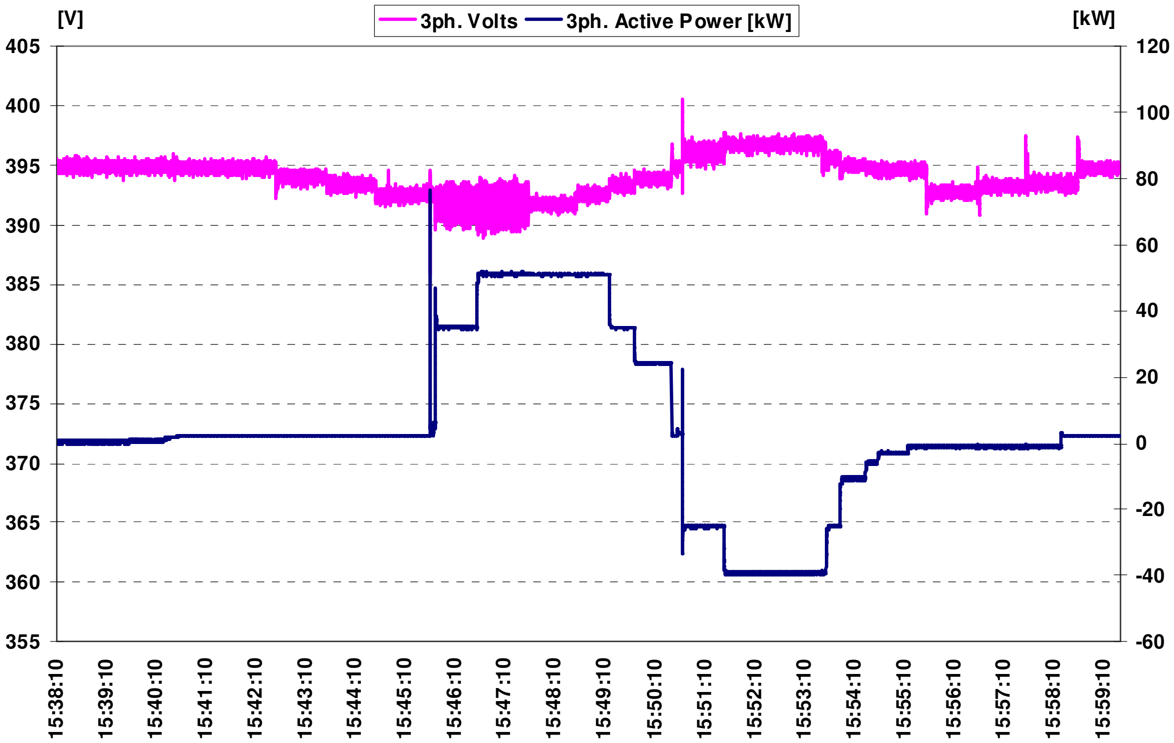


Figure 3.27 – Test 1: three phase voltage and active power measured at the terminals of the Redox battery converter.

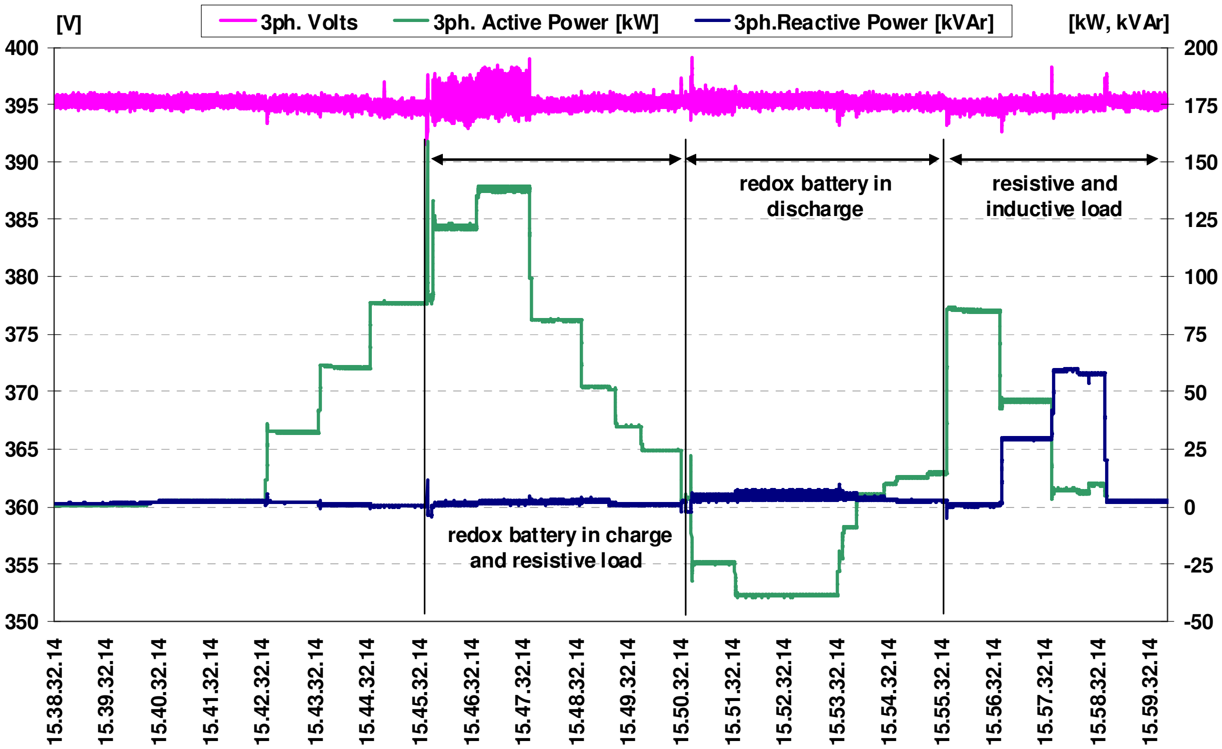


Figure 3.28 – Test 1: three phase voltage and active power measured at the terminals of the I-power Converter.

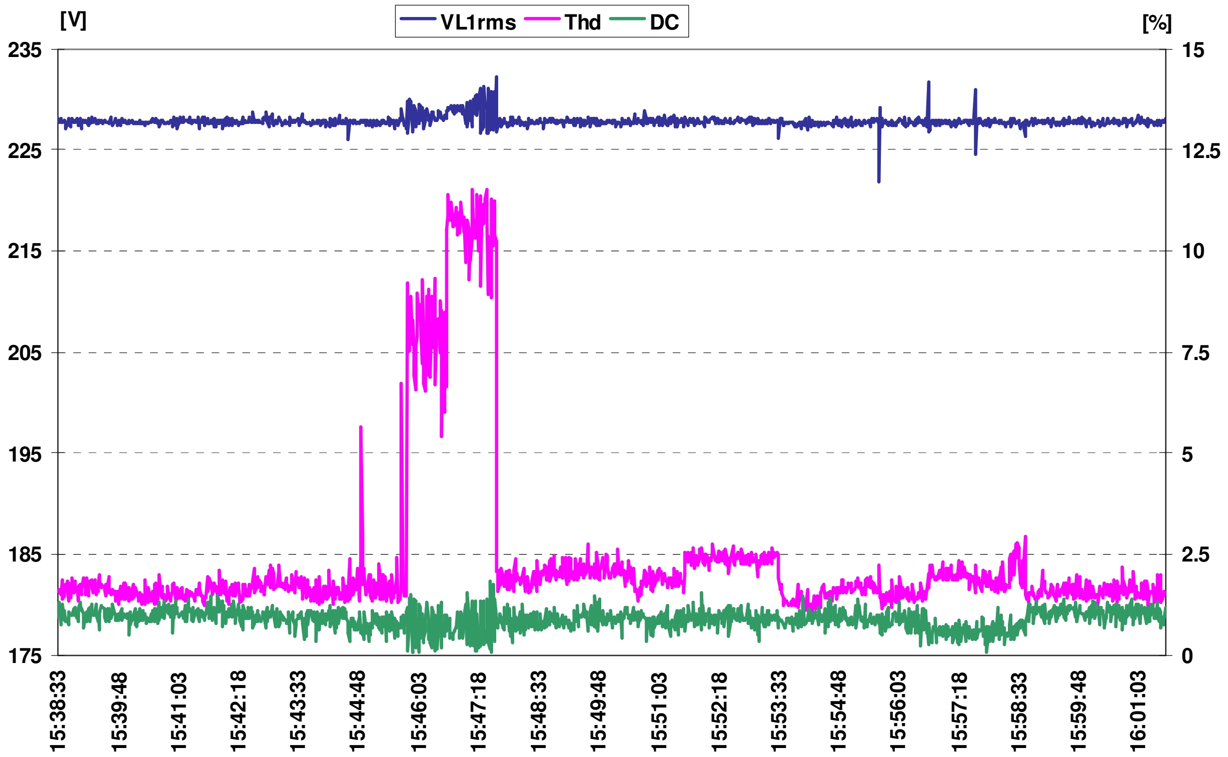


Figure 3.29 – Test 1: THD, DC component and RMS value of L1 phase voltage on busbar 2.

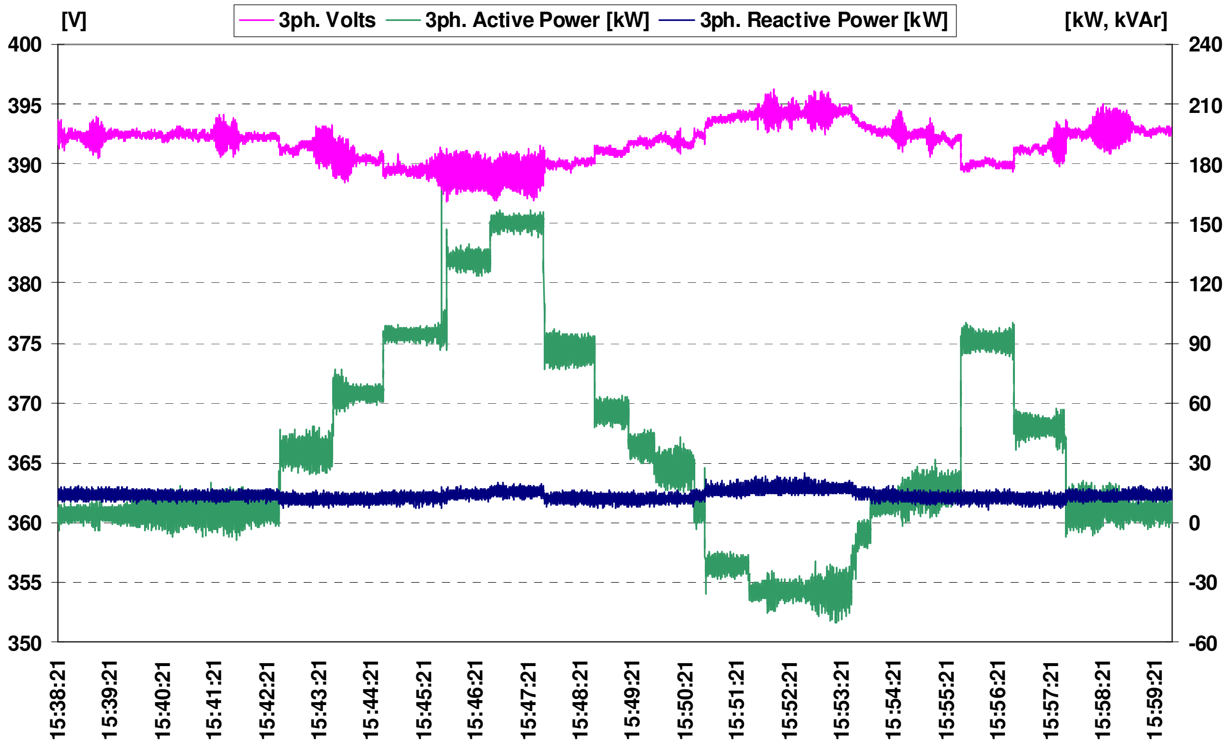


Figure 3.30 – Test 1: three phase voltage and active power measured at the busbar 1.

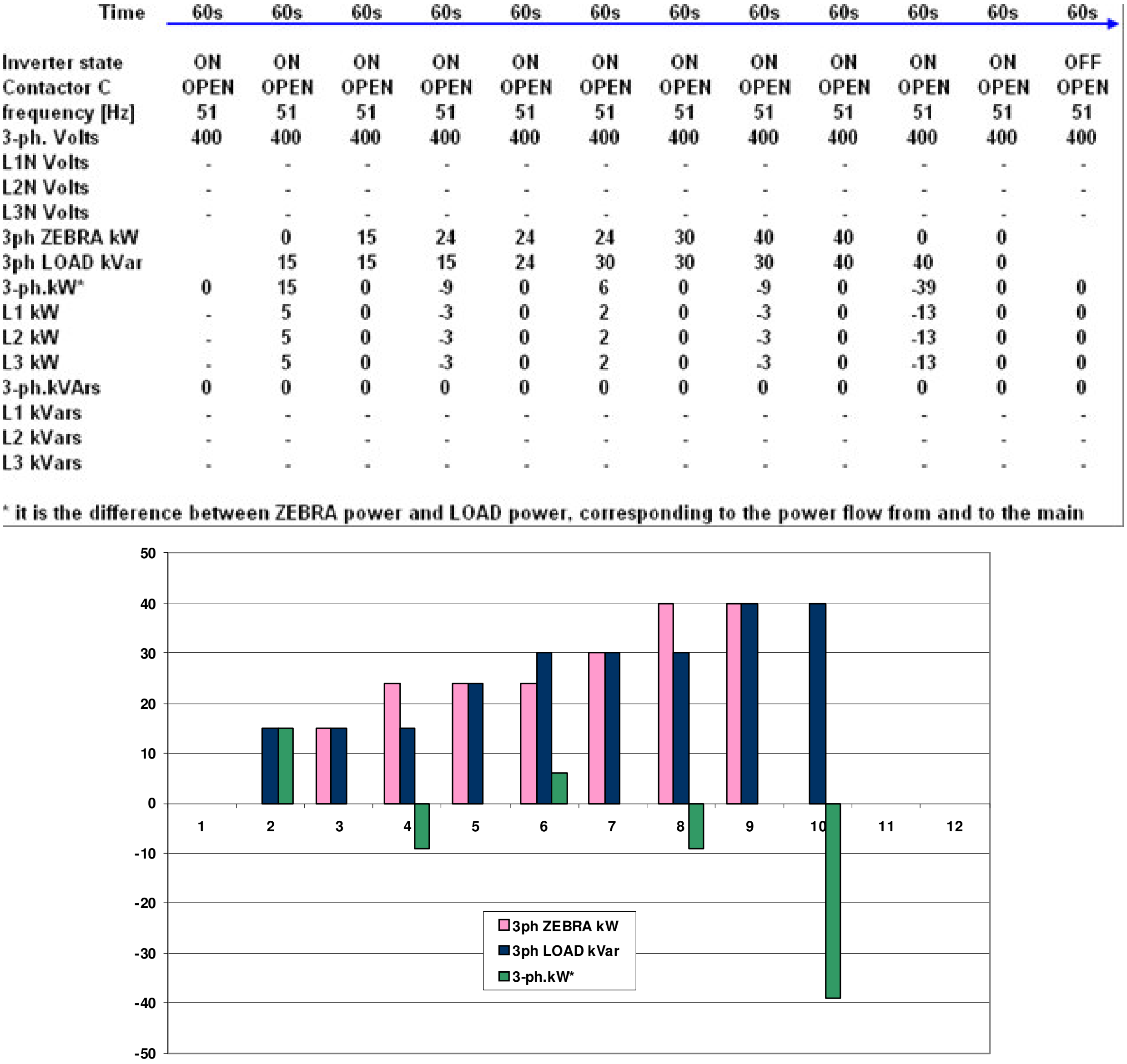
3.5 Balancing of active and reactive power during this “VIRTUAL ISLANDING” (NO power flow TO and FROM main grid)

During this test the I-power inverter supplies the ZEBRA battery storage system and the programmable load, connected on the busbar 2. ZEBRA battery inverter operates as a generator (ZEBRA battery is in discharge mode). The aim of this test was to balance load and generation on busbar 2 in order to obtain no power flow to and from the main grid. The purpose was to analyze the ability of the inverter to supply very little loads.

3.5.1 Test 1: Balancing of active and reactive power

Test setting

The measurement instruments, set up as shown in Figure 3.31, were used in PowerMeter mode configuration. The parameters measured included 3phase voltages, phase-to-neutral voltages, frequency, active and reactive power and currents for each phase.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
Contactor C	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
frequency [Hz]	51	51	51	51	51	51	51	51	51	51	51	51
3-ph. Volts	400	400	400	400	400	400	400	400	400	400	400	400
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-
3ph ZEBRA kW		0	15	24	24	24	30	40	40	0	0	
3ph LOAD kVar		15	15	15	24	30	30	30	40	40	0	
3-ph.kW*	0	15	0	-9	0	6	0	-9	0	-39	0	0
L1 kW	-	5	0	-3	0	2	0	-3	0	-13	0	0
L2 kW	-	5	0	-3	0	2	0	-3	0	-13	0	0
L3 kW	-	5	0	-3	0	2	0	-3	0	-13	0	0
3-ph.kVArs	0	0	0	0	0	0	0	0	0	0	0	0
L1 kVars	-	-	-	-	-	-	-	-	-	-	-	-
L2 kVars	-	-	-	-	-	-	-	-	-	-	-	-
L3 kVars	-	-	-	-	-	-	-	-	-	-	-	-

* it is the difference between ZEBRA power and LOAD power, corresponding to the power flow from and to the main

Figure 3.31 – Test 1: Balancing of active and reactive power during this “virtual islanding” (NO power flow)

Test results

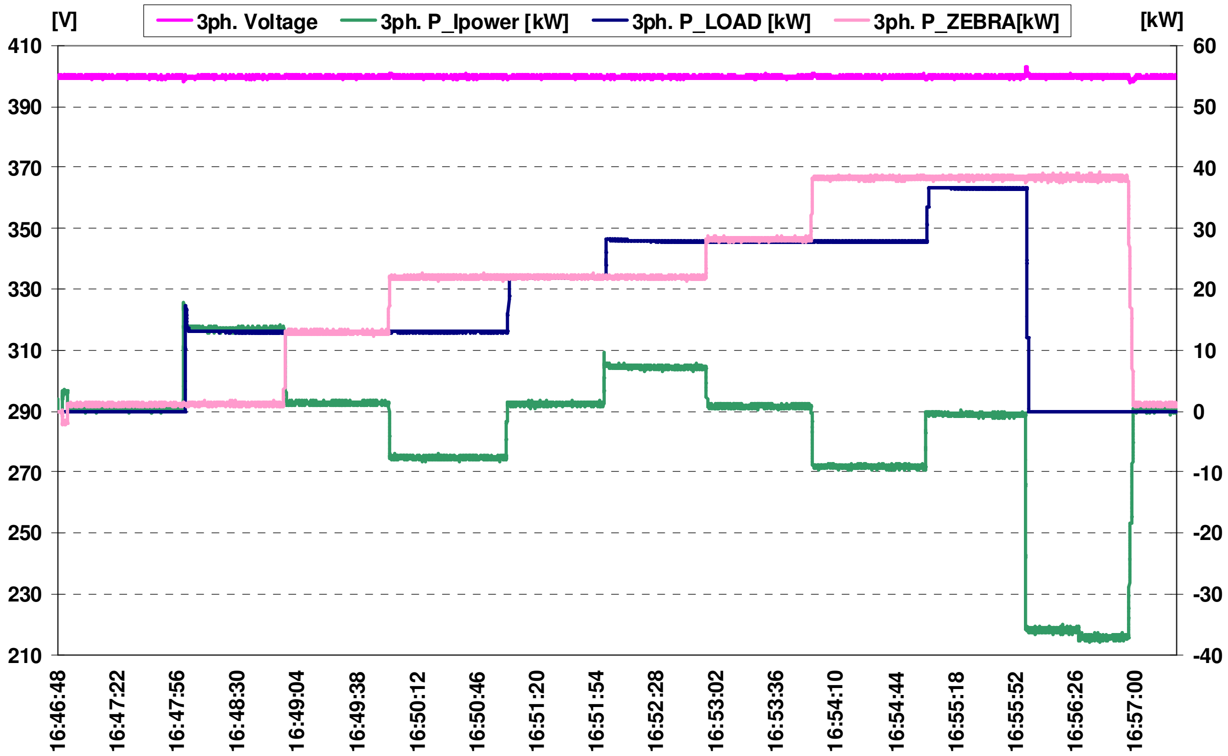


Figure 3.32 – Test 1: three-phase voltage, load active power, ZEBRA inverter active power and I-Power active power.

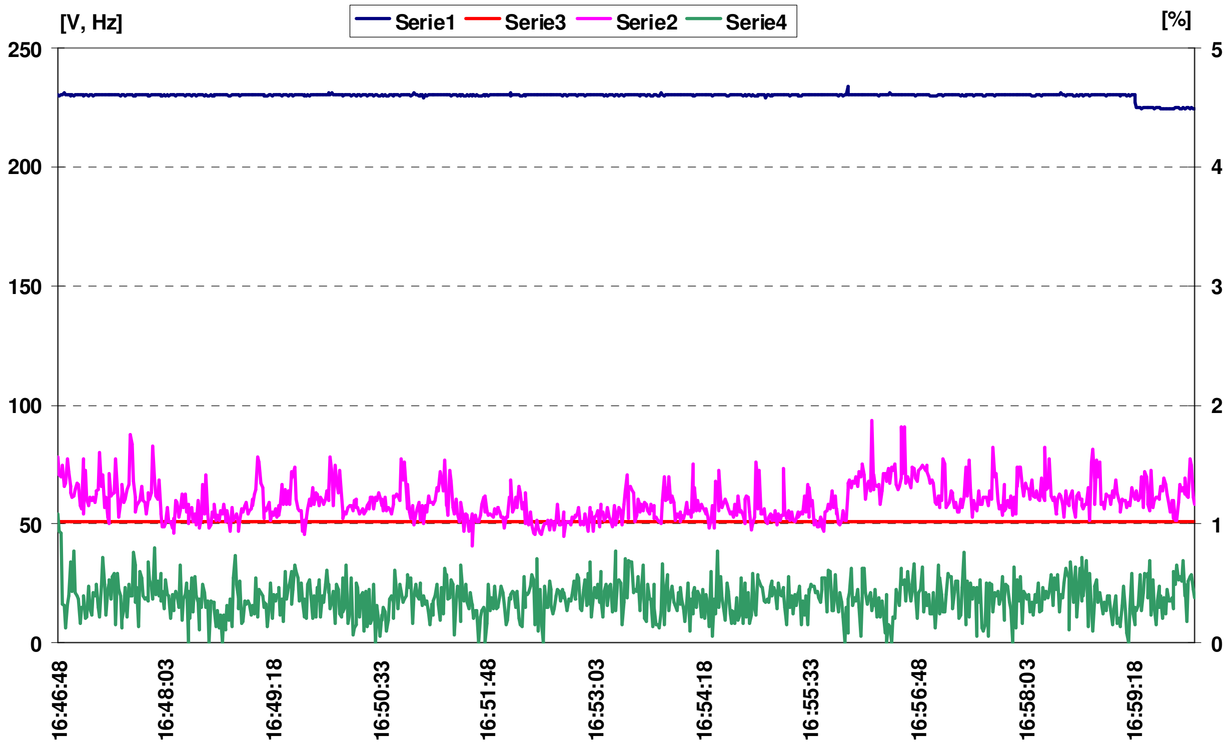


Figure 3.33 – Test 1: THD, DC component and RMS value of the L1 phase voltage on busbar 2.

3.6 Transition test

As described in the section 2.1, when the bypass breaker is open the inverter transfers power between the LV distribution grid and the micro-grid. In this situation the inverter operates as a voltage generator and it is possible to operate the micro-grid independently, with a different voltage and frequency.

When you close the bypass breaker you establish a direct connection between the main grid and the microgrid. When the operator commands the transition from microgrid to grid, the inverter will re-synchronise with the grid frequency (see Figure 3.34), and adjust the voltages to achieve a balance. Once this is achieved, the inverter reverts to become a current source inverter again, and sends a signal to the breaker requesting it to close. Once the breaker is closed, the inverter power transfer will be reduced to zero and the power flows only through the bypass connection.

The aim of the transition tests, described in the following paragraphs, is to analyze both the performance of the inverter during the transitory phase of transfer and the action of the micro during this period.

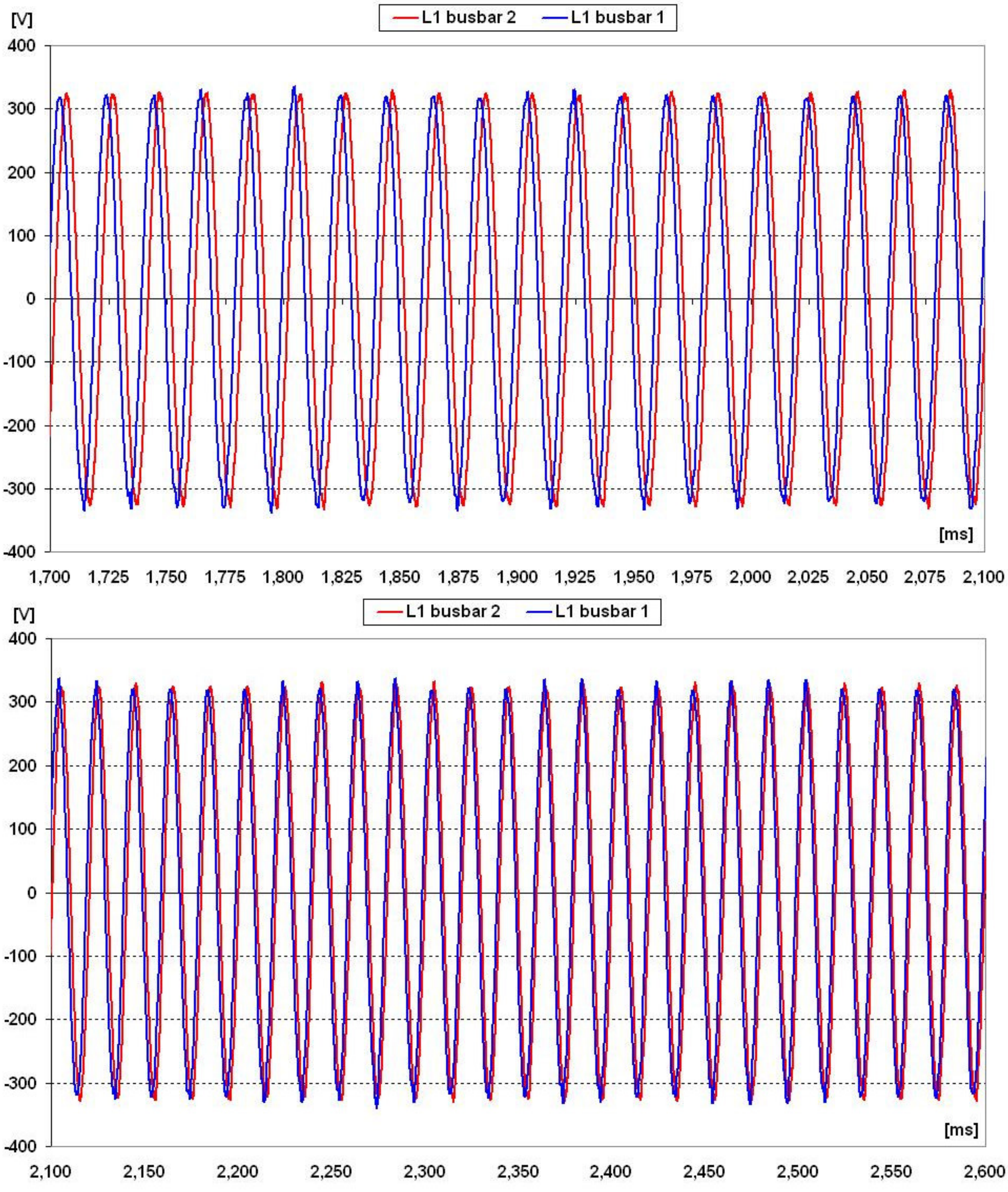
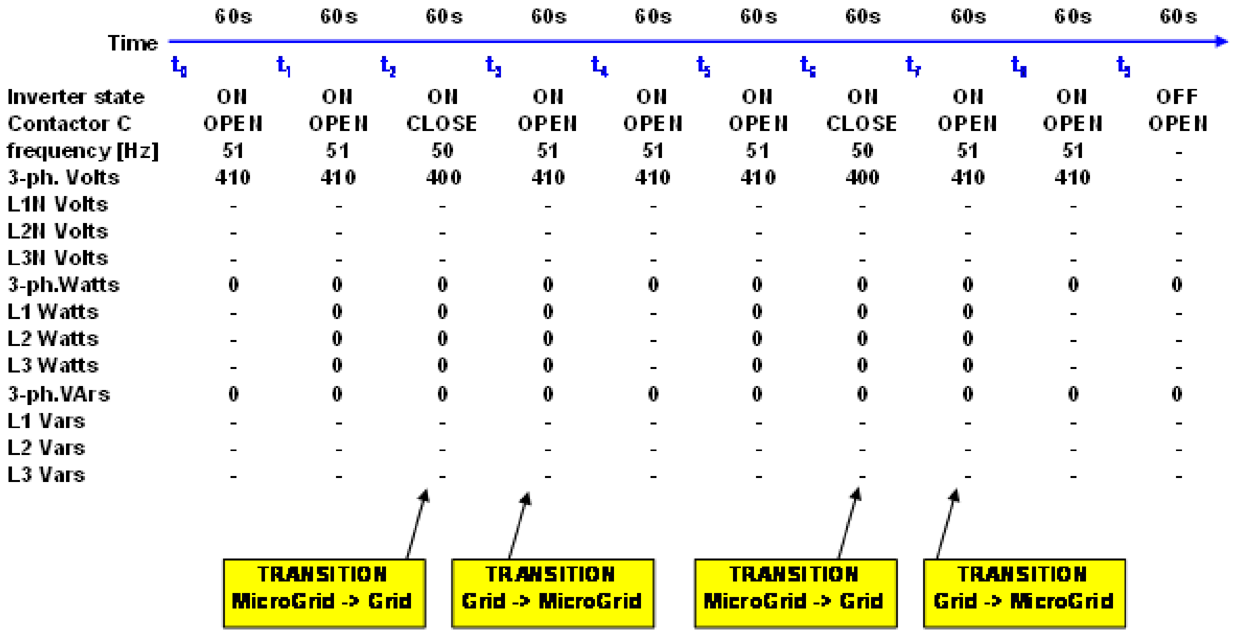


Figure 3.34 – Voltage L1 of the microgrid (measured on busbar 2) and of the main grid (measured on busbar 1) during the synchronization operation before the closing of the bypass breaker.

3.6.1 Test 1: transition with no transfer of power from the main grid

Test setting

The measurement instruments, settled as shown in Figure 3.35, have been used in PowerMeter mode configuration. The inverter supplies busbar 2 with a stable voltage of 400 V_{RMS} and a frequency of 51 Hz, with an unbalanced load or generation. We measured 3phase voltages, phase-to-neutral voltages, frequency, active and reactive power and currents of each phase.



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF
Contactor C	OPEN	OPEN	CLOSE	OPEN	OPEN	OPEN	CLOSE	OPEN	OPEN	OPEN
frequency [Hz]	51	51	50	51	51	51	50	51	51	-
3-ph. Volts	410	410	400	410	410	410	400	410	410	-
L1N Volts	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-
3-ph.Watts	0	0	0	0	0	0	0	0	0	0
L1 Watts	-	0	0	0	-	0	0	0	-	-
L2 Watts	-	0	0	0	-	0	0	0	-	-
L3 Watts	-	0	0	0	-	0	0	0	-	-
3-ph.VArs	0	0	0	0	0	0	0	0	0	0
L1 Vars	-	-	-	-	-	-	-	-	-	-
L2 Vars	-	-	-	-	-	-	-	-	-	-
L3 Vars	-	-	-	-	-	-	-	-	-	-

Figure 3.35 – Test 1: Transition with no transfer of power to and from the main grid.

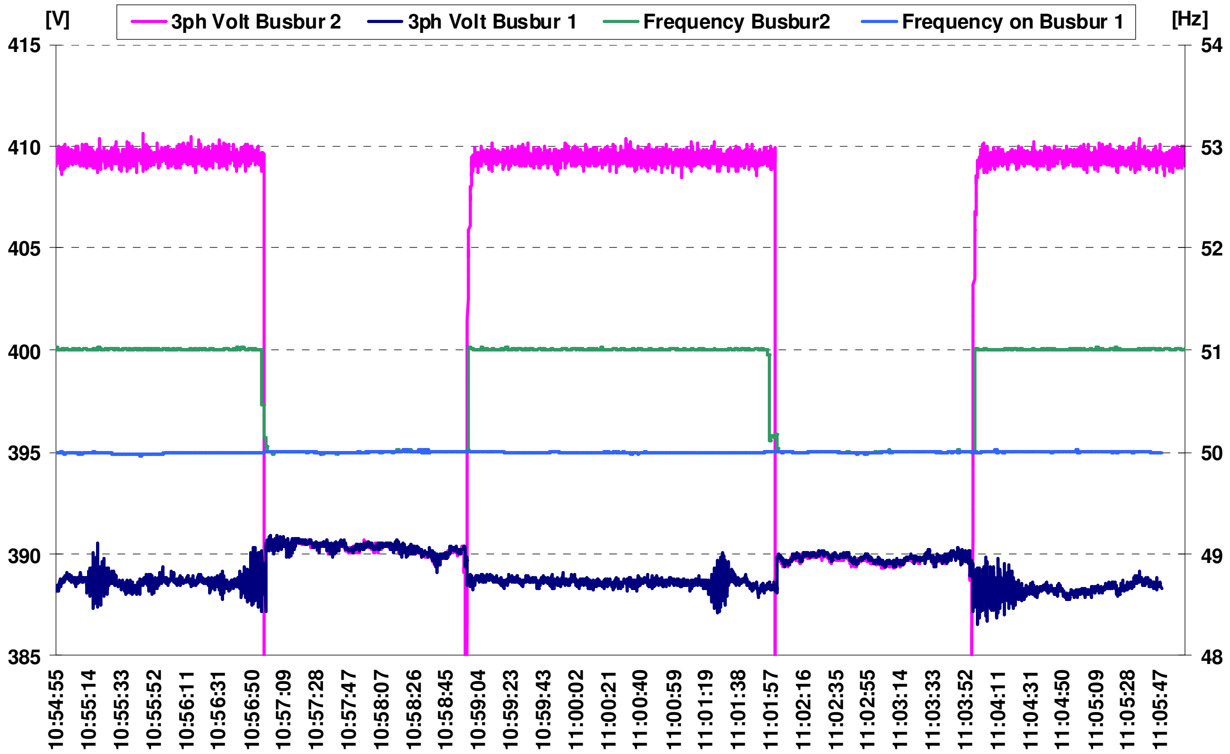


Figure 3.36 – Test 1: Three-phase RMS voltage and frequency on busbar 1 and busbar 2 during a transition test with no transfer of power between grid and microgrid.

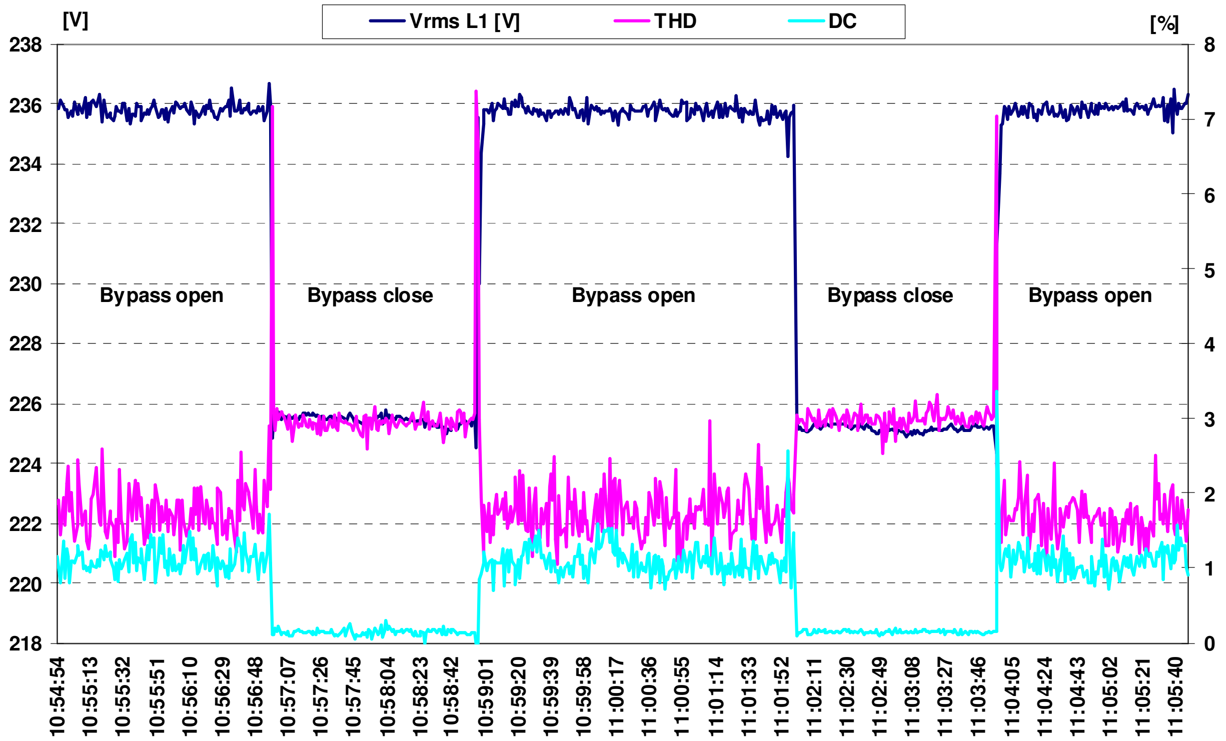
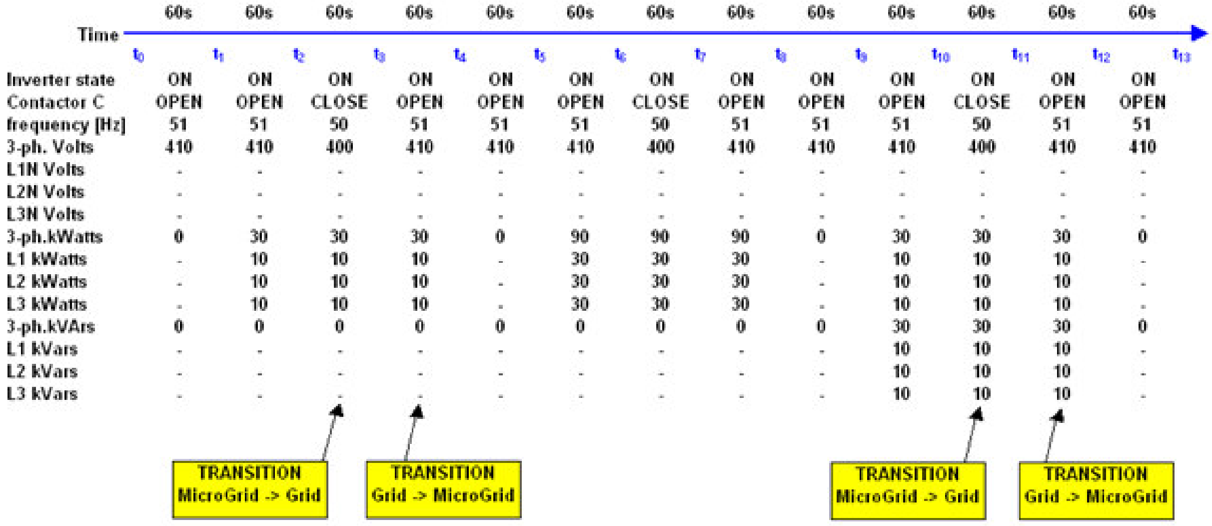


Figure 3.37 – Test 1: THD, DC component and RMS value of the L1 phase voltage on busbar 2.

3.6.2 *Test 2: transition with transfer of active & reactive power from the "main grid"*

Test setting



Time	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s	60s
Inverter state	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
Contactor C	OPEN	OPEN	CLOSE	OPEN	OPEN	OPEN	CLOSE	OPEN	OPEN	OPEN	CLOSE	OPEN	OPEN
frequency [Hz]	51	51	50	51	51	51	50	51	51	51	50	51	51
3-ph. Volts	410	410	400	410	410	410	400	410	410	410	400	410	410
L1N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L2N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
L3N Volts	-	-	-	-	-	-	-	-	-	-	-	-	-
3-ph.kWatts	0	30	30	30	0	90	90	90	0	30	30	30	0
L1 kWatts	-	10	10	10	-	30	30	30	-	10	10	10	-
L2 kWatts	-	10	10	10	-	30	30	30	-	10	10	10	-
L3 kWatts	-	10	10	10	-	30	30	30	-	10	10	10	-
3-ph.kVArs	0	0	0	0	0	0	0	0	0	30	30	30	0
L1 kVars	-	-	-	-	-	-	-	-	-	10	10	10	-
L2 kVars	-	-	-	-	-	-	-	-	-	10	10	10	-
L3 kVars	-	-	-	-	-	-	-	-	-	10	10	10	-

Figure 3.38 – Test 2: Transition with no transfer of power to and from the main grid.

Test results

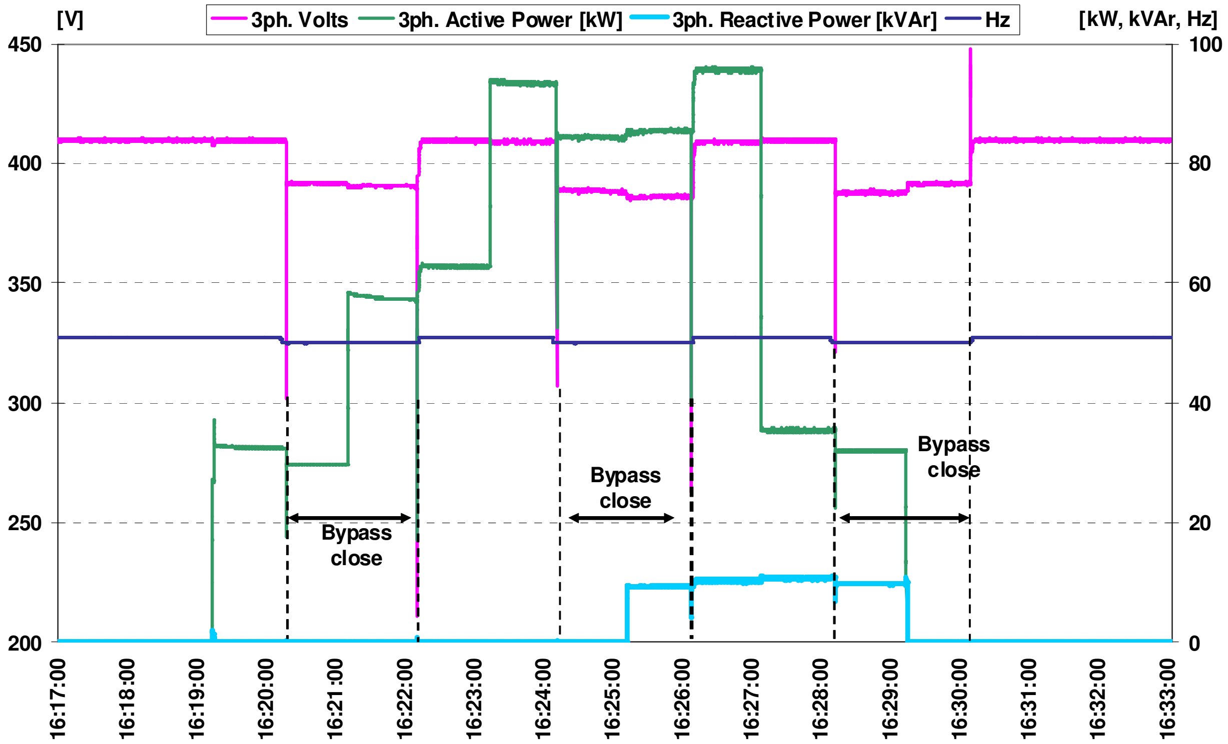


Figure 3.39 – Test 2: Frequency, three-phase RMS voltage, active and reactive power measured on busbar 2, after the filter, during the test of transition with transfer of power from grid to microgrid.

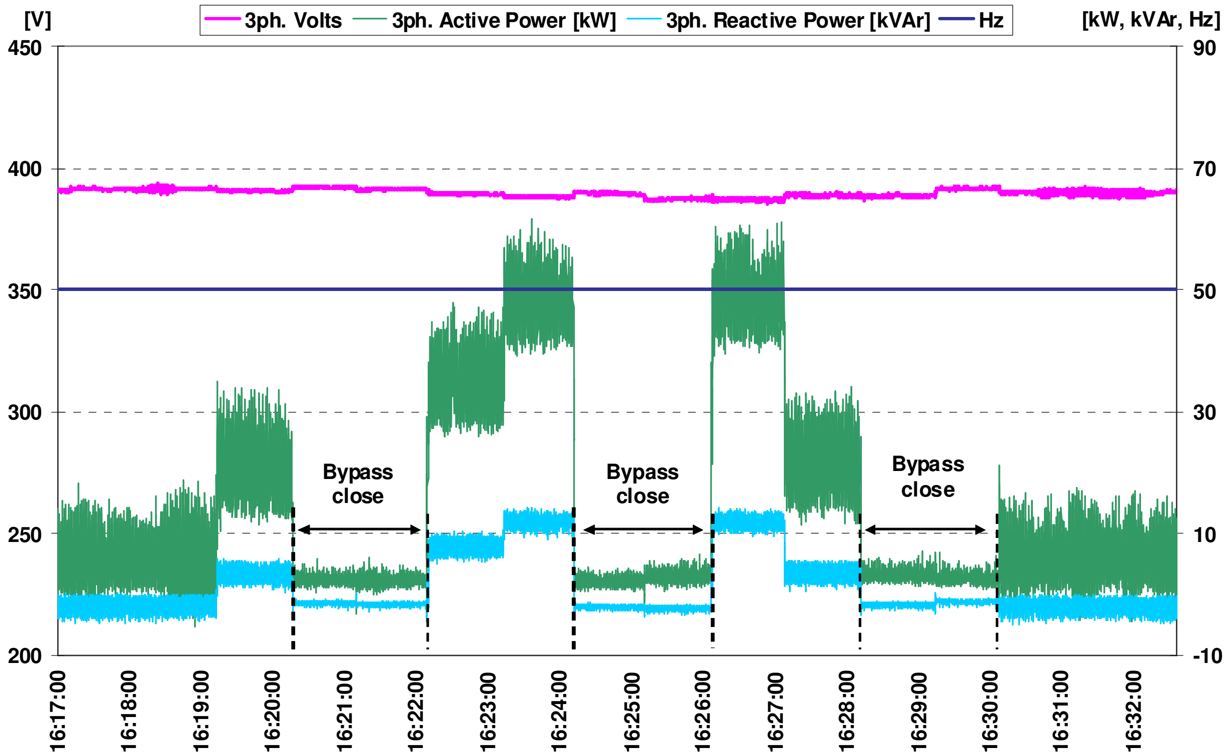


Figure 3.40 – Test 2: frequency, three-phase voltage, active and reactive power measured on busbar 1, inlet of transformer, during the test of transition with transfer of power from grid to microgrid

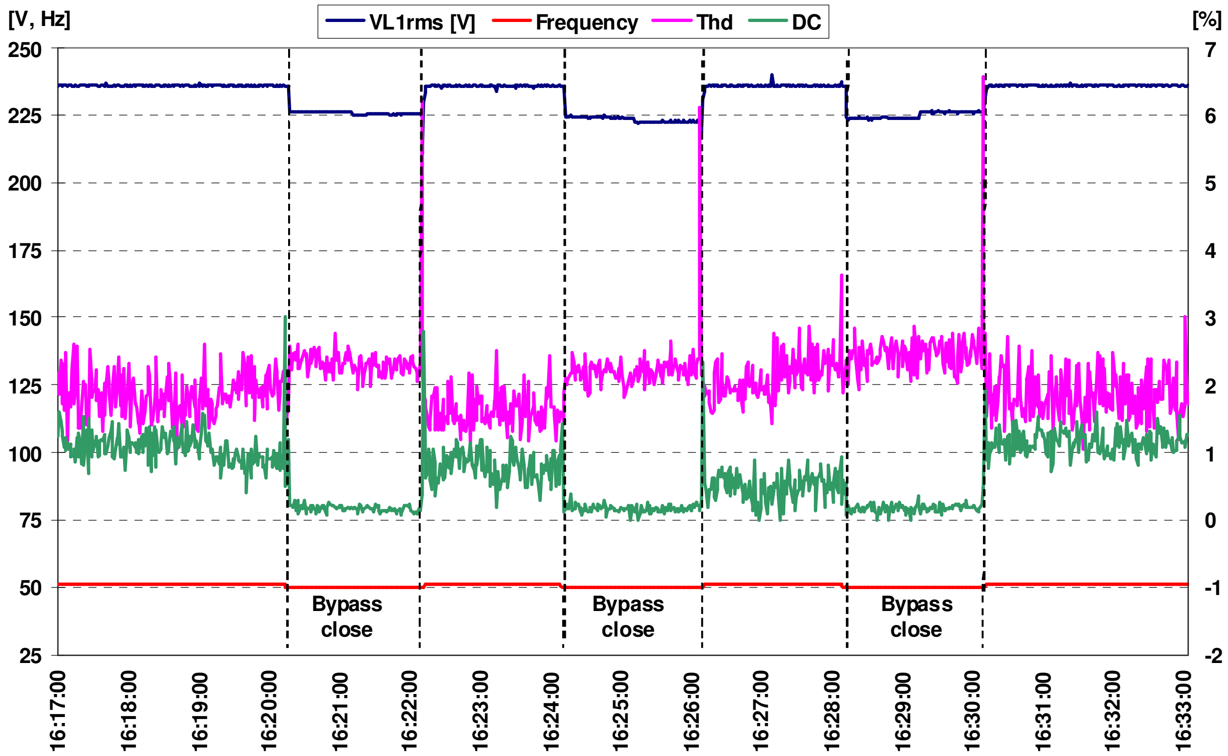


Figure 3.41 – Test 2: THD, DC component and RMS value of the L1 phase voltage on busbar 2.

3.6.3 Transient analysis

The following chart shows the voltages during the closing of the bypass occurred at about 7720 ms. During the transition you can see a drop of the inverter voltage. After the closing we measured an increase of THD of the grid voltage (from 1% to 2%), it decreases again after a short period.

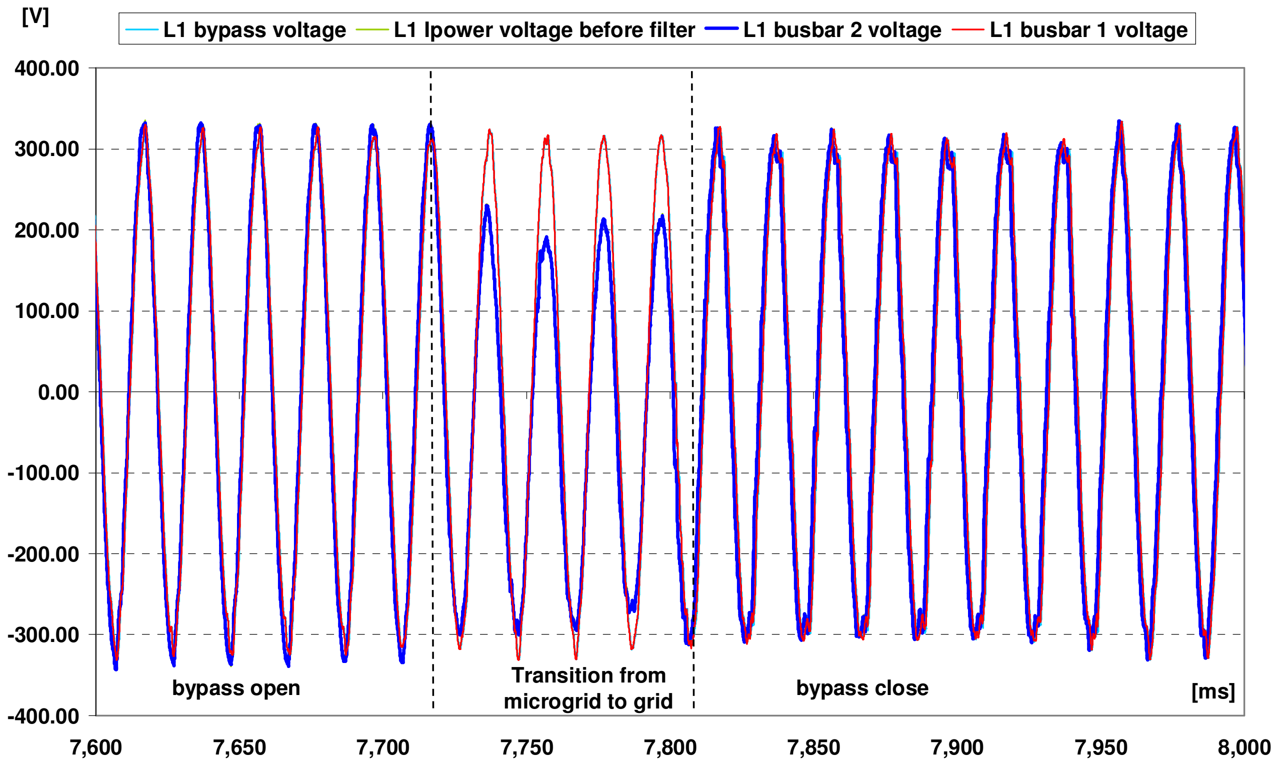


Figure 3.42 – Voltage L1 measured on busbar 2, at the output of the I-power inverter after the filter, and on busbar 1, at the inlet of the transformer, during the closing of the bypass breaker.

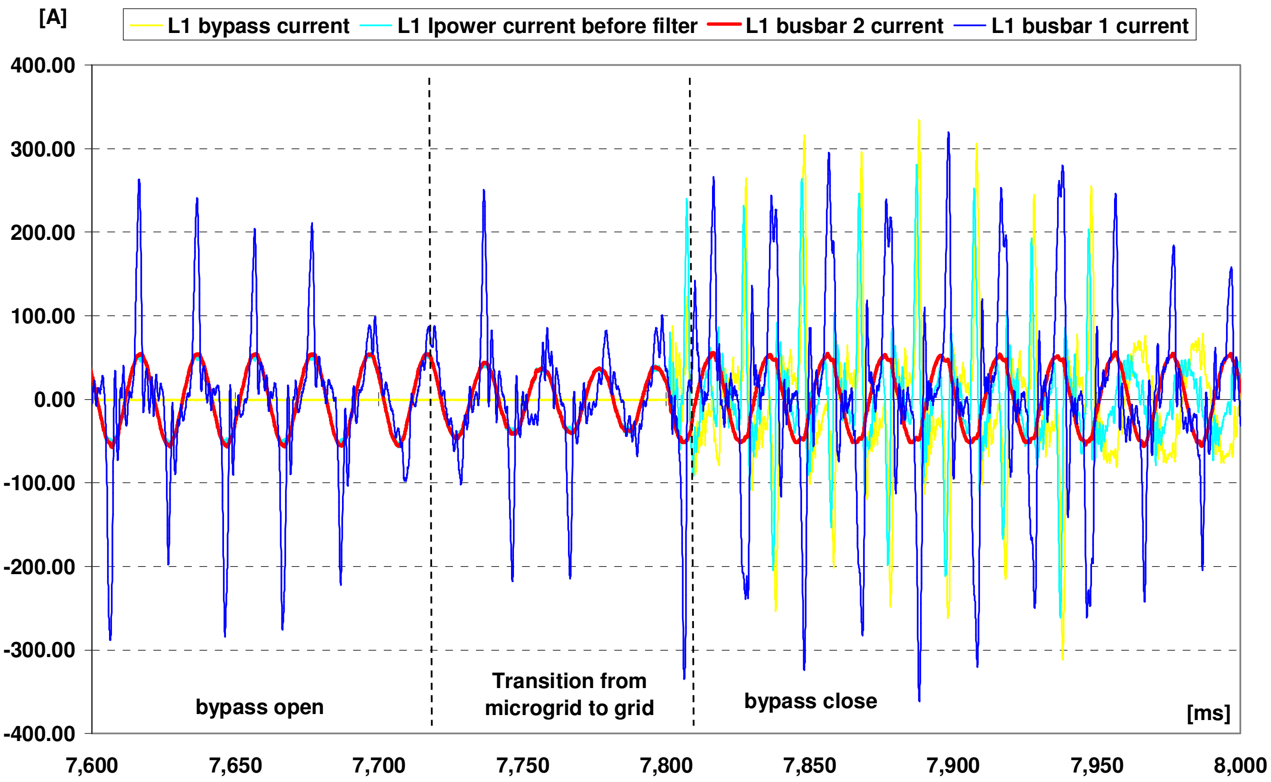


Figure 3.43 – Current L1 measured on Bypass line, on busbar 2 after the filter, on busbar 1 at the inlet of the transformer, on the output of the inverter before the filter during the closing of bypass.

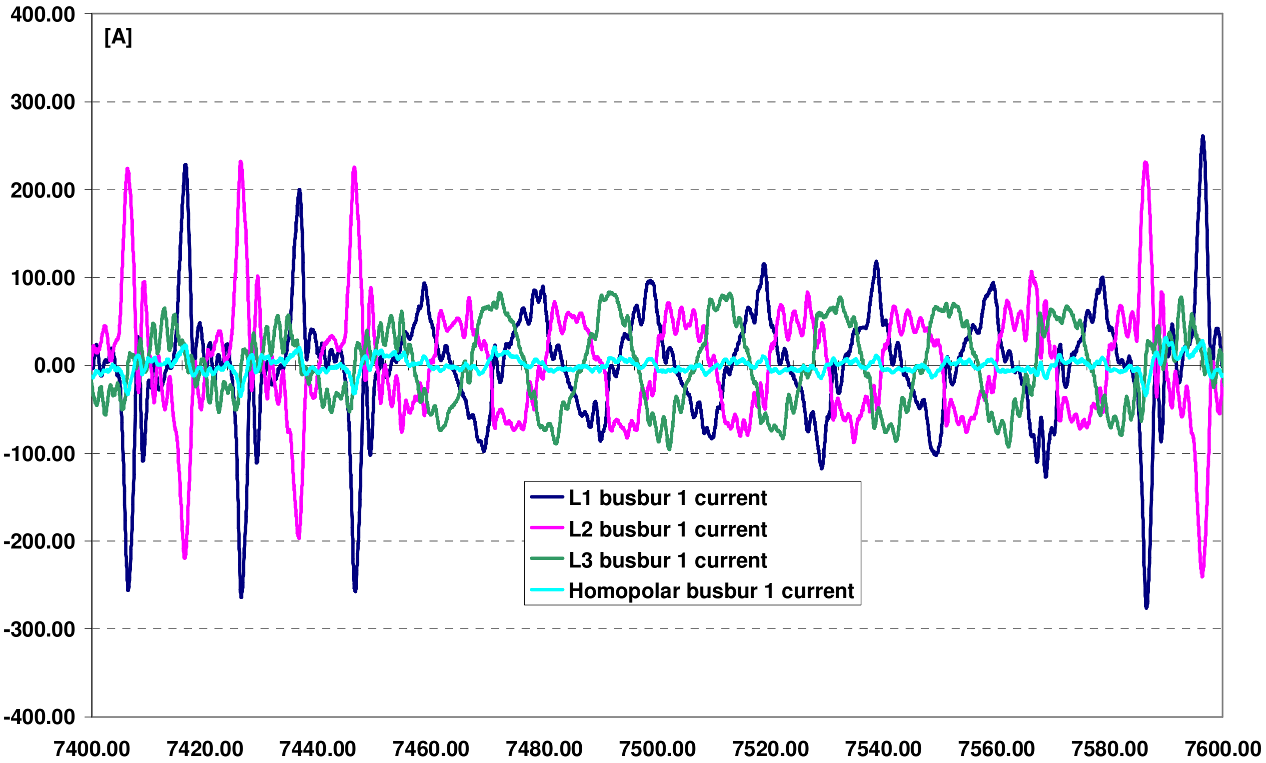


Figure 3.44 – Currents L1, L2, L3 at the inlet of the transformer on busbar 1 (main grid) during the closing of bypass.

The chart below shows the opening of the bypass breaker and the transition from main-grid to microgrid. The inverter voltage during the transitory is very disturbed (there is a continuous component of 56%) and the THD of the grid voltage (line blue) is very high just before the opening (about 6%).

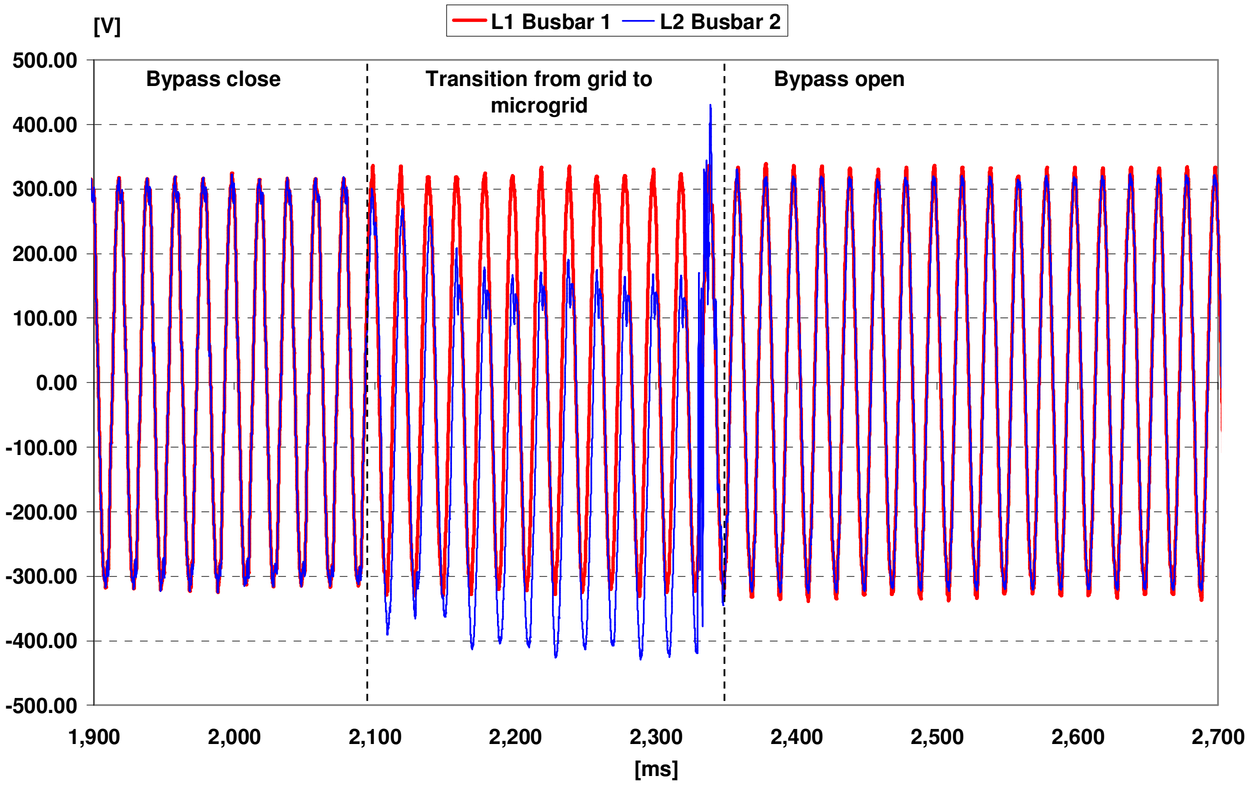


Figure 3.45 – Voltage L1 measured on busbar 2, at the output of the I-power inverter after the filter, and on busbar 1, at the inlet of the transformer, during the opening of the bypass breaker.

3.6.4 Comments

An investigation has been initiated into the causes of instability, the main findings to date can be summarised as follows.

Components & Control: A set of mechanical breakers have been used in the system due to low cost and low loss but problems have been identified which arise from uncertainty in breaker timing.

Issues are also suspected with the inverters changing mode, the grid linked inverter is typically configured to be a current source inverter and the Islanded inverter has to have the characteristics of both voltage and current source. This can lead to problems with harmonics, reactive power requirements and the island detection system.

4 CONCLUSIONS

Workpackage F Task 7 has successfully implemented a virtual microgrid under laboratory conditions, this has allowed the examination and investigation of several Microgrid topologies and generation scenarios under well defined steady state and transient network situations.

The main conclusions that have been reached are that with steady state conditions, Microgrids are well behaved and can usefully complement the network operation, however under transient conditions of transferring to and from grid for islanding operation, issues affecting overvoltage on the Microgrid can arise which leads to concern. This has been recently re-enforced by the publication in Spain [1] of a paper, which discusses similar problems and has produced major safety issues, when disconnecting a number of independent solar inverters.

The engineers involved in this EU Project are also directly involved in assessing and writing International and National Standards, and the test facility is being used to assess, verify and modify existing and proposed test procedures. The work done in MORE Microgrids will feed directly into the relevant IEC and National Standards Committees

5 REFERENCES

[1] "Power Frequency Overvoltages Generated by Solar Plants". Publication, by Iberdrola,

[2] EN50160 – Voltage characteristics in public distribution systems.