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Technical Report TA User Project

MGCS-LTV

Microgrid Control System Laboratory Testing and Validation

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Abbreviations

<i>CHIL</i>	Controller Hardware-in-the-Loop
<i>DER</i>	Distributed Energy Resource
<i>DSM</i>	Demand Side Management
<i>MGCS</i>	Microgrid Control System
<i>POC</i>	Point of Connection (of microgrid to the public grid)
<i>PV</i>	Photovoltaic
<i>TA</i>	Trans-national Access

Table 1: Symbols

Symbol	Unit	Description
$P_{LOAD,start}$	kW	Load power before the step
$P_{LOAD,end}$	kW	Load power after the step
ΔP_{LOAD}	kW	Delta power before and after the step
$P_{inv\ 1,droop}$	kW	Power of inverter 1 after the droop control set-point adjustment
$P_{inv\ 2,droop}$	kW	Power of inverter 2 after the droop control set-point adjustment
$P_{inv\ 1,settled}$	kW	Power of inverter 1 after the secondary control set-point adjustment
$P_{inv\ 2,settled}$	kW	Power of inverter 2 after the secondary control set-point adjustment
$f_{max/min}$	Hz	Maximum / minimum frequency after the step
$f_{delta,max,Step}$	Hz	Difference between maximum and minimum frequency
$U_{settled\ 10s\ avg}$	V	Voltage after the secondary control set-point adjustment as 10 s average
$U_{max,Step\ 10s,avg}$	V	Maximum voltage after the step as 10s average
$U_{min,Step\ 10s,avg}$	V	Minimum voltage after the secondary control set-point adjustment as 10 s average
t_d	s	Delay time
t_s	s	Settling Time

Description of variable names in the measurement plots

Table 2: Variables in measurement plots

Variable name	Unit	Description	Sample rate
INV_1/P_H1per	kW	Output power of inverter 1	1 period
INV_2/P_H1per	kW	Output power of inverter 2	1 period
INV_1/Q_H1per	kW	Reactive power of inverter 1	1 period
INV_2/Q_H1per	kW	Reactive power of inverter 2	1 period
LOAD/P_H1per	kW	Total load power	1 period
LOAD/P_L1	kW	Load power phase L1	10 periods
LOAD/P_L2	kW	Load power phase L2	10 periods
LOAD/P_L3	kW	Load power phase L3	10 periods
POC/Frequency	Hz	Frequency at the POC (microgrid side)	
GRD/Frequency	Hz	Frequency of the utility grid	
f_min	Hz	Bottom threshold for frequency band	/
f_max	Hz	Top threshold for frequency band	/
f_nom	Hz	Nominal frequency 50 Hz	/
POC_Tol_b	kW	Bottom threshold for grid power at POC	/
POC_Tol_up	kW	Top threshold for grid power at POC	/
POC/P_H1per	kW	Active power at POC	1 period
POC/U_H1per	V	Voltage at POC	1 period
POC/U_L1_H1per	V	Voltage phase L1 at POC	1 period
POC/U_L2_H1per	V	Voltage phase L2 at POC	1 period
POC/U_L3_H1per	V	Voltage phase L3 at POC	1 period
POC/U_rms_L1	V	Voltage phase L1 at POC	10 periods
POC/U_rms_L2	V	Voltage phase L2 at POC	10 periods
POC/U_rms_L3	V	Voltage phase L3 at POC	10 periods
POC/Q_H1per	kVA	Total reactive power at POC	1 period
Connection Switch	-	1 = POC breaker is closed (grid connected mode) 0 = POC breaker is open (islanded mode)	
POC/I_L1	A	Transient current phase L1 at POC	20 kHz
POC/I_L2	A	Transient current phase L2 at POC	20 kHz
POC/I_L3	A	Transient current phase L3 at POC	20 kHz
INV1/I_L1	A	Transient current of inverter 1 at phase L1	20 kHz
INV1/I_L2	A	Transient current of inverter 1 at phase L2	20 kHz
INV1/I_L3	A	Transient current of inverter 1 at phase L3	20 kHz
INV2/I_L1	A	Transient current of inverter 2 at phase L1	20 kHz
INV2/I_L2	A	Transient current of inverter 2 at phase L2	20 kHz
INV2/I_L3	A	Transient current of inverter 2 at phase L3	20 kHz
INV/I_L1	A	Transient current of inverter 1 and inverter 2 at phase L1	20 kHz
INV/I_L2	A	Transient current of inverter 1 and inverter 2 at phase L2	20 kHz
INV/I_L3	A	Transient current of inverter 1 and inverter 2 at phase L3	20 kHz
INV/I_In_tot	A	Transient current of inverter 1 and 2, neutral line	20 kHz

Executive Summary

Over the last years the role of microgrids have been increasing steadily and they will play a more important role in future power grids with the aim to provide a more resilient electricity supply. Microgrids are usually low-voltage networks, which can operate grid-connected or isolated from the main grid. The microgrid control system manages the transition between grid-connected and islanded mode and is also responsible for energy dispatch functions. Testing this control system is crucial for safe and reliable operation of microgrids. Thus, IEEE-SA published the IEEE 2030.8-2018 – *Standard for the Testing of Microgrid Controllers* in August 2018. It provides a test methodology for the verification and quantification for the performance of different microgrid controller functions. Within this transnational access the usability and applicability of the standard is validated by laboratory tests in the *Smart Grid Technologies Laboratory (SGTL)* of *TECNALIA*, in Spain. Therefore, test and experiment specifications according to the ERIGrid holistic test specification templates were written and lab tests conducted following them. In this report experiences and lessons from the tests, as well as measurement results are presented.

General Information of the TA User Project

Project Information

User Project title	Microgrid Control System Laboratory Testing and Validation
User Project acronym	MGCS-LTV
Keywords	Microgrids, interoperability, compliance testing, standardization
Host research infrastructure	TECNALIA (Smart Grid Technologies Laboratory)
Access period	2019/05/06 – 2019/05/31

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1 Research Motivation

The role of microgrids increased steadily over the last years and will play an important role in future electricity grids with the aim to provide a more reliable and stable electricity supply. *The microgrid exchange group of the U.S. Department* defines a microgrid within the IEEE 2030.7 standard for microgrid control system [2] as follows:

“A microgrid is as group of interconnected loads and distributed energy resources with clearly defined electric boundaries. It can connect and disconnect from the grid and operate in grid-connected and island modes. A microgrid control system is used to coordinate the components of a microgrid for generation, storage and demand, as well as for the transition from grid to grid connected modes.

A first approach for specific microgrid testing procedures is given by IEEE in the standard IEEE2030.8 [3], published on 14th June 2018. It provides testing procedures for the core functions of microgrids specified within IEEE 2030.7. The test methodology validates proper functionality for the transition between grid-connected and islanded mode, as well as energy dispatch functions at the point of interconnection. As the standard is relatively young not much information about its applicability is given. Hence, further research is envisaged to validate the applicability of the test methodology and eventually find critical situations in microgrids which possible lead to a test failure.

A lack of standardization for microgrids is observed in European regulatory framework but also on an international level. For instance, standardization work for microgrids is also done by the IEC system evaluation group SEG 6. Some of their aims are the identification of the standardization status regarding microgrids and the identification of use cases and specific needs for the microgrid technology and standardization gaps. A first task was a worldwide online survey which specific questions related to microgrids. One outcome was that around 74% of the participants find that current international standards do not meet the requirements for developing microgrids and need further improvement [4]. Hence, the motivation of the proposed work is also to give inputs for future standardization at a European and on an international level.

1.1 Objectives

As the testing framework of IEEE 2030.8 is quite young (June 2018) only limited experience about its feasibility and applicability is given. The main objective of this work is to validate the testing procedures against reproducibility and integrity. Possible gaps in the standard and potential for improvement shall be looked up. Therefore, extensive testing is done on a microgrid in a laboratory environment. The tests itself shall also uncover possible weaknesses and challenges for microgrid controllers.

1.2 Scope

Testing according the recently published standard IEEE 2030.8 is done in the laboratory. The microgrid laboratory of TECNALIA provides ideal possibilities to setup different microgrid configurations regarding connected distributed energy resources (DER), loads, line impedances as well low-level control parametrization sets of inverters and high-level control strategies of the microgrid control system. The microgrid control system which is tested was developed at a time when no standardization for microgrid controllers (e.g. IEEE 2030.7) was available. Additionally, it was developed and is used only for research purposes and not as a commercial industrial product. It is expected that the tests may look up critical issues of conventional microgrids already in operation.

2 State-of-the-Art

Microgrids are defined by the U.S. Department of Energy (Microgrid Exchange Group) as group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode [2] [5]. The European Technology Platform for the *Electricity Networks of the Future (SmartGrids)* defines them as low voltage networks with distributed generation (DG), together with local storage devices and controllable loads (e.g. water heaters and air conditioning). They operate mostly connected to the distribution network, but they can be automatically transferred to islanded mode, in case of faults in the upstream network and can be resynchronized after restoration of the upstream network voltage [5].

Microgrids are facing numerous technical challenges. Therefore, a lot of research is ongoing and promising solutions are proposed and demonstrated worldwide. These efforts resulted also in the development of international standards, mostly related to the planning, operation and protection schemes for micro grids [6] [7]. To name some of them:

- IEC TS 62898-1 Guidelines for microgrid projects planning and specification [6]
- IEC TS 62898-2 Microgrids Guidelines for Operation, working document [6]
- IEC TS 62898-3-1 Microgrids–Technical/protection Requirements, working document [6]
- IEEE 1547.4 - Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems [7]
- IEEE P1547-REV Microgrid Connection to Distribution Utilities; Microgrid/Dist' Utility, ISO/RTO [6]
- IEEE2030.9 IEEE Recommended Practice for the Planning and Design of the Microgrid (2019)
- IEEE P2030.10 -Standard for DC Microgrids for Rural and Remote Electricity Access Applications [6]
- IEEE P2030.9 –Recommended Practice for the Planning and Design of the Microgrid [7]
- IEC TS 62257 Series [1] - Recommendations for renewable energy and hybrid systems for rural electrification

The key component of the microgrid is the microgrid control system (MGCS). It performs energy dispatch functions and controls the transition between grid-connected and island mode as well as the reconnection. The different control functions can be distinguished into primary and secondary control, e.g. local frequency and voltage control and tertiary control e.g. economic and optimized operation or other dispatch functions for managing electricity imports and exports between the microgrid and the utility grid. Different control principles as central-based, local/autonomous (droop control method), or agent-based may be used in the microgrid [8].

Due to this complexity, IEEE introduced the IEEE 2030.7 standard, which tries to define the basic functionalities of a microgrid control system. The recently published standard IEEE 2030.8 offers corresponding testing procedures for the MGCS. The aim of the standard is to define the testing framework, including initial conditions, initiation events and required procedures to characterize and validate the controller operations and functionality of microgrid controllers specified at the point of connection (POC) to the utility grid. The standard does not define the structure and components of the microgrid, nor the communication system or protection schemes [3]. The standard's test portfolio is given in Table 3. The standard provides a methodology to test the MGCS for different scenarios and to test different microgrid configurations regarding stability and safe operation.

Table 3: Test portfolio IEEE2030.8 [3], [6]

<i>Dispatch function tests</i>	<i>Transition/dispatch tests</i>
Defines the set-point of DERs and controllable loads in grid connected and islanded modes <ul style="list-style-type: none">• Steady State, grid connected scenarios• Steady state, islanded scenarios	Defines the controller operation in transition from grid connected to islanded mode and reconnection <ul style="list-style-type: none">• Planned islanding test• Unplanned islanding test• Reconnection test

3 Test Case Descriptions

The first part of this ERIGrid TA was to define test case descriptions which map the test portfolio in the standard. The descriptions follow *ERIGrids holistic test specification templates* and are in principle independent on the MGCS under test and the lab where the test were conducted¹. A test case consists of several tests and each test has a test specification. Chapter 0 describes the lab setup and the performed tests which are a subset of the ones listed in this chapter.

Five main test scenarios are defined in IEEE 2030.8:

1. Steady State Islanding
2. Steady State Grid Connected
3. Planned Islanding
4. Unplanned Islanding
5. Reconnection

Each test scenario/case requires the definition of test specifications with concerns to the microgrid under test. The test specifications are based on initial conditions and initiating events. Initial conditions can be a base load, state of the Point of Connection (POC) breaker, grid exchange power etc. An initiating event can be a change of load or generation power, DER trips, requests for islanding or reconnection. The test engineer defines quantitative and qualitative metrics e.g. settling time according to IEEE 2030.8 recommendations. This work introduces a variety of possible MGCS test specifications given in Table 4.

Table 4: Generated test specifications for the five IEEE 2030.8 test scenarios (ar. = arbitrary) [1]

Test case	Initiating Event	Initial Conditions			Metrics	
		$P_{Load, Base}$	P_{POC}	Available Gen. \geq Demand	Response, settling time (t_r , t_s) for:	Qualitative metrics
Steady-state Islanding	Largest Load Step - 3 phase symmetrical	✓	0	✓	Frequency (f)	Steady state values, dispatch objectives within contractual requirements and equipment limitations not exceeded
	Largest Load Step - unsymmetrical	✓	0	✓	f	
	Largest Load Step - symmetrical or unsymmetrical	✓	0	x	f	
	Largest reactive load - inductive and capacitive	✓	0	✓	Voltage (U)	
	Trip of large DER	✓	0	✓	f	
	Trip of large DER	✓	0	x	f	
	DER Steps - Change of DER output power	✓	0	✓	f	
	Energy Storage Limitations – Fully charged storage	✓	0	✓	f	
	Energy Storage Limitations – Fully discharged storage	✓	0	✓	f	
Steady-state grid-connected	Largest Load Step - symmetrical or unsymmetrical	✓	0	✓	Power at POC (P_{POC})	Steady-state values, dispatch objectives within contractual requirements and equipment limitations not exceeded
	Largest Load Step - symmetrical or unsymmetrical	✓	-	✓	P_{POC}	
	Largest Load Step - symmetrical or unsymmetrical	✓	+	✓	P_{POC}	
	Trip of large DER	✓	0	✓	P_{POC}	
	Energy Storage Limitations – Fully charged storage	✓	0	✓	P_{POC}	
	Energy Storage Limitations – Fully discharged storage	✓	0	✓	P_{POC}	
	Compliance to national grid connection rules / initial conditions as required by the specific technical rules	according to standard			-	
Planned Islanding	Planned islanding signal is sent	✓	0	✓	f	Frequency / voltage and equipment limitations not exceeded during transition
	Planned islanding signal is sent	✓	+	✓	f	
	Planned islanding signal is sent	✓	-	✓	f	
	Planned islanding signal is sent	✓	ar.	x	f	

¹ To clarify the wording: the standard uses the phrase test scenario while the holistic test specification templates mentions test cases. Reference to the standard uses the naming of the standard, the tables based on the templates the wording from the templates, which is on the one hand consistent, on the other hand could lead to confusions.

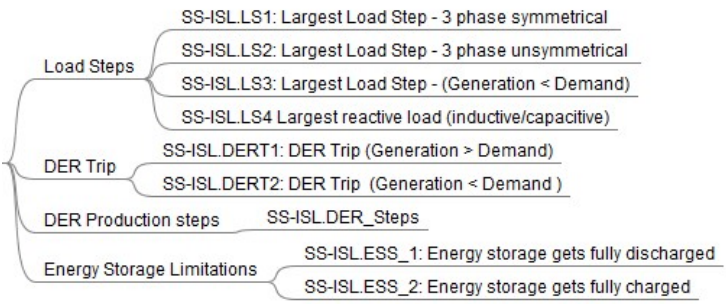
Test case	Initiating Event	Initial Conditions			Metrics	
		$P_{Load, Base}$	P_{POC}	Available Gen. \geq Demand	Response, settling time (t_r , t_s) for:	Qualitative metrics
Unplanned Islanding	Outage of the main grid (by use of an AC simulator of dedicated POC breaker)	✓	ar.	✓	f	Is a microgrid formed
	Automatic transition to island mode is required due to a critical utility grid situation (f, U, power quality, etc.)	✓	ar.	✓	f	Does the POC breaker open?
Reconnection	Reconnection signal sent	✓	ar.	✓	P_{POC}	Time to reconnect
	Automatically reconnect due to critical islanded microgrid situation (f, U, power quality, etc.)	✓	ar.	ar.	P_{POC}	

Not all the introduced tests could be tested in the laboratory because of time and equipment limitations during the ERIGrid TA. The tests are included in the table for the sake of completeness and for possible future experiments as support for test engineers involved in IEEE2030.8 testing.

3.1 SS-ISL: Steady State Islanding

Table 5 shows the test case description for Steady State Islanding following ERIGrid's test case description templates [9].

Table 5: Test case description – Steady State Islanding

Name of the Test Case	SS-ISL Steady State Islanding
Narrative	<p>The tests are done when the microgrid is operated in islanded mode (POC breaker open) and verify the dispatch functionality and ability of the MGCS to recover its frequency after deviations, caused by changes in load demand or generation. The scenarios consist of symmetrical and unsymmetrical load steps and DER trips. The tests verify if the microgrid control system is able to restore stable, steady state operation after disturbances as changing generation e.g. due to available solar irradiance, wind etc. or changing load power. Another aim is to verify if frequency and voltage requirements are maintained and equipment limitations not exceeded. The developed test scenarios are shown in Figure 1. For microgrids with large energy storage two additional scenarios are introduced. The first scenario tests the behavior of the microgrid when the storage gets empty and cannot be discharged anymore and the second when the storage gets fully charged and DER energy cannot be stored anymore, shall be tested.</p>  <p>Figure 1: Test scenarios for SS-ISL: Steady State Islanding</p>

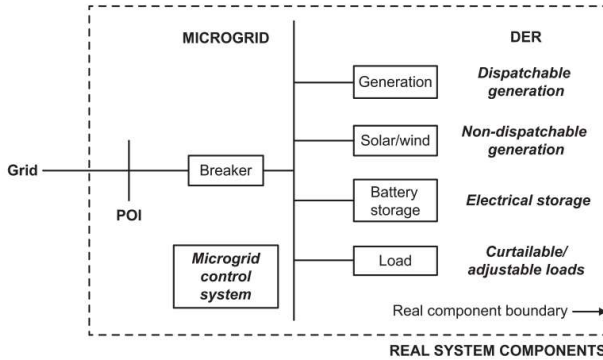
Function(s) under Investigation (FuI) "the referenced specification of a function realized (operationalized) by the object under investigation"	<ul style="list-style-type: none"> - Individual dispatch functions - Frequency and voltage recovery after load steps etc.
Object under Investigation (Oul) "the component(s) (1...n) that are to be qualified by the test"	Microgrid Control System (MGCS)
Domain under Investigation (Dul): "the relevant domains or sub-domains of test parameters and connectivity."	<ul style="list-style-type: none"> • Control algorithm • Power • Communication
Purpose of Investigation (Pol) The test purpose in terms of Characterization, Verification, or Validation	<ul style="list-style-type: none"> • Characterization of the performance – response and settling time until the frequency is recovered after a disturbance. • Verification if the microgrid stays in islanded mode and frequency and voltage limits are not exceeded. • Validation if the dispatch objective is maintained e.g. power is set by the MGCS accordingly to a specific strategy as reducing electricity costs etc.
System under Test (SuT): Systems, subsystems, components included in the test case or test setup.	Microgrid: Inverters, energy storage system, breaker at the point of interconnection, loads, generators, synchronization unit etc.
Functions under Test (FuT) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. Oul and SuT.	Droop control secondary control in interaction with generators
Test criteria: Formulation of criteria for each Pol based on properties of SuT; encompasses properties of test signals and output measures.	<ul style="list-style-type: none"> - Frequency enters tolerance band $\pm X$ mHz (10 mHz are chosen within this work) - Power set points of the generators are set accordingly to the individual dispatch objective (e.g. set points according to price optimization, increase share of renewable generation etc.)
target metrics Measures required to quantify each identified test criteria	<ul style="list-style-type: none"> - Response time for the microgrid frequency (time until the frequency enters the tolerance band the first time. In Figure 2 from the IEEE2030.8 standard it is defined as time until 90% of the power value is reached. As there is no power at the POC in islanded mode it would be necessary to measure it for each DER. To reduce the effort the microgrid frequency is chosen as

	<p>variable for the settling time.)</p> <ul style="list-style-type: none"> - Settling time for the microgrid frequency <p>Figure 5—Depiction of a representative response of P and Q controllers at the POI</p> <p>Figure 2: Determination of response and settling time according to IEEE2030.8 [3]</p>
<p>quality attributes threshold levels for test result quality as well as pass/fail criteria.</p>	<p>Allowable control deadband: $\pm X$ mHz of nominal frequency (levels are defined by microgrid operator, owner etc.)</p>

3.1.1 SS-ISL.LS1: Steady State Islanding - Largest Load Step – 3 phase symmetrical

The test verifies if the frequency in the microgrid is kept within the required tolerance band after a large symmetrical load is switched on. The second objective validates if individual dispatch objectives of the microgrid are maintained by the MGCS.

Table 6: Test Specification SS-ISL.LS1

Reference to Test Case	SS-ISL
Title of Test	SS-ISL.LS1: Steady State Islanding - Largest Load Step – 3 phase symmetrical
Specific Test System	 <p>Figure G.6—Final commissioning field testing block diagram example</p> <p>Figure 3: Test system according to IEEE 2030.8 – Breaker is open for this test [3]</p>
Target measures	<ol style="list-style-type: none"> 1. Is the μ-grid operating after the load step? Are frequency and voltage within its operational range? 2. How long is the time until voltage and/or frequency reaches a stable operating point e.g. recovery to nominal value (Δf and ΔU within defined tolerance band by the involved parties or test engineer) 3. Are the power levels of DER and loads as expected according to a certain dispatch objective e.g. individual bidding schemes for the marginal costs?
Input and output parameters	<p>Controllable input parameters</p> <ul style="list-style-type: none"> - Load - POC breaker - Marginal price of bidding scheme <p>Uncontrollable input parameters</p> <ul style="list-style-type: none"> - Power output of non-controllable DER <p>Measured parameters</p> <ul style="list-style-type: none"> - Frequency - Power (voltage, current) of DER
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in islanded mode, according to “initial system state” description 2. A base load is on. If possible the sum of the base- and largest load should correspond to the maximum available generation of controllable and uncontrollable DER. 3. Turn on the largest symmetrical load of the μ-grid 4. Wait until the system reaches a steady state (frequency enters and stays in specified tolerance band) 5. Turn off largest load 6. Wait until the system reaches a steady state

	<i>Repeat step 3 to 6 at least 3 times.</i>
Initial system state / Initial conditions	<ul style="list-style-type: none"> - The system is operating in steady state islanded mode - POC breaker is open - A symmetrical base load is on (see test design) - DERs, including energy storage systems have enough reserve to supply additional load in the range of largest load
Temporal resolution	<i>100 ms for continuous data collection of power values according to IEEE 2030.8</i>
Suspension criteria / Stopping criteria	<i>Voltage/frequency are not reaching a steady state</i> <i>Note: Tripping of grid forming device would be a valid test result</i>

3.1.2 SS-ISL.LS2: Steady State Islanding - Largest Load Step – 3 phase unsymmetrical

The test is identical to SS-ISL.SL1 except that an unsymmetrical load is used. It verifies, if the generation in the microgrid can supply unsymmetrical load demand.

Table 7: Test Specification SS-ISL.LS2

Reference to Test Case	<i>SS-ISL</i>
Title of Test	<i>SS-ISL.LS2: Steady State Islanding - Largest Load Step – 3 phase unsymmetrical</i>
Specific Test System	<i>Same as for SS-ISL.LS1</i>
Target measures	<i>Same as for SS-ISL.LS1</i>
Input and output parameters	<i>Same as for SS-ISL.LS1</i>
Test Design	<i>Same as for SS-ISL.LS1, except that an unsymmetrical load is used.</i>
Initial system state / Initial conditions	<i>Same as for SS-ISL.LS1, except that an unsymmetrical load is used.</i>
Evolution of system state and test signals	<i>N/A</i>
Other parameters	<i>N/A</i>
Temporal resolution	<i>Same as for SS-ISL.LS1</i>
Source of uncertainty	<i>N/A</i>
Suspension criteria / Stopping criteria	<i>Same as for SS-ISL.LS1</i>

3.1.3 SS-ISL.LS3: Steady State Islanding - Largest Load Step – (Generation < Demand)

The test is identical to SS-ISL.LS1 but for this case the maximum generation of controllable and non-controllable DER is not sufficient for supplying the load demand. In this case either the frequency or voltage within the microgrid leaves the required specifications or the microgrid stops. If the specific microgrid can shed loads or a storage can be discharged the microgrid should be able to continue proper operation. Alternatively, the microgrid could switch into grid-connected mode, but this should be tested within a separate test scenario and this option not be activated within this scenario.

Table 8: Test Specification SS-ISL.LS3

Reference to Test Case	SS-ISL
Title of Test	SS-ISL.LS3: Steady State Islanding - Largest Load Step – (Generation < Demand)
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<ul style="list-style-type: none"> - <i>Is the microgrid still in operation and within the specifications of voltage and frequency</i> <ul style="list-style-type: none"> ○ <i>Was a reconnection to the utility grid necessary?</i> ○ <i>Are loads shed?</i> ○ <i>Is a storage discharged? (if available)</i> ○ <i>Determine response and settling time according to SS-ISL.LS1.</i>
Input and output parameters	<i>Same as in SS-ISL.LS1</i>
Test Design	<i>Same as in SS-ISL.LS1</i>
Initial system state	<ul style="list-style-type: none"> - <i>The system is operating in steady state islanding mode</i> - <i>POC breaker is open</i> - <i>A symmetrical base load is on (see test design)</i> - <i>DERs do not have enough reserve to supply additional load in the range of largest load</i>
Evolution of system state and test signals	<i>Same as in SS-ISL.LS1</i>
Other parameters	<i>Same as in SS-ISL.LS1</i>
Temporal resolution	<i>Same as in SS-ISL.LS1</i>
Source of uncertainty	Scenario might not be applicable for each microgrid and laboratory setup due to limitations of the maximum available load.
Suspension criteria / Stopping criteria	<i>Same as in SS-ISL.LS1</i>

3.1.4 SS-ISL.LS4: Steady State Islanding - Largest reactive load (inductive/capacitive)

This test scenario validates if the microgrid can maintain large reactive loads as motors. The test principle is the same as for SS-ISL.LS1 but with reactive loads.

Table 9: Test Specification SS-ISL.LS1

Reference to Test Case	<i>SS-ISL</i>
Title of Test	<i>SS-ISL.LS4: Steady State Islanding - Largest reactive load (inductive/capacitive)</i>
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<i>Same as in SS-ISL.LS1</i>
Input and output parameters	<i>Same as in SS-ISL.LS1 including a reactive load as controllable input parameter</i>
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in islanded mode, according to “initial system state” description 2. A resistive base load is on 3. A reactive inductive base load is on 4. Largest reactive inductive load of μ-grid is turned on 5. Wait until the system reaches a steady state 6. Turn off largest inductive load 7. Wait until the system reaches a steady state 8. Repeat step 4 to 7 at least three times <p><i>Repeat step 3 to 8 with the largest capacitive load</i></p>
Initial system state / Initial conditions	<i>Same as in SS-ISL.LS1, and a reactive base load is turned on.</i>
Evolution of system state and test signals	<i>N/A</i>
Other parameters	<i>N/A</i>
Temporal resolution	<i>Same as in SS-ISL.LS1</i>
Source of uncertainty	<i>Same as in SS-ISL.LS1</i>
Suspension criteria / Stopping criteria	<i>Same as in SS-ISL.LS1</i>

3.1.5 SS-ISL.DERT1: Steady State Islanding – DER Trip (Generation > Demand)

The test verifies if the microgrid can handle the loss of generation power e.g. because of a trip of DER's. For this test it is expected that other controllable and non-controllable DER have enough resources to supply the load demand.

Table 10: Test Specification SS-ISL.DERT1

Reference to Test Case	SS-ISL
Title of Test	SS-ISL.DERT1: Steady State Islanding – DER Trip (Generation > Demand)
Specific Test System	Same as in SS-ISL.LS1
Target measures	Same as in SS-ISL.LS1
Input and output parameters	Same as in SS-ISL.LS1
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in islanded mode according to “initial system state” description 2. Set load that controllable DER to be tripped operates at 20% of nominal power. 3. Tripping of DER 4. Wait until the system reaches steady state again <p>Repeat steps 2 to 4 in 20% power steps until nominal power of DER to be tripped is reached</p> <p>Note: The DER is controllable and adjusts its power to the load demand. Further optional tests can be done with non-controllable DER</p>
Initial system state	<ul style="list-style-type: none"> - The system is in islanded mode - Non-grid forming DER are operating - The DER that will trip is operating at 20% of nominal power - All other generators can take over the generation of the DER that will trip.
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	Same as in SS-ISL.LS1
Source of uncertainty	Same as in SS-ISL.LS1
Suspension criteria / Stopping criteria	Same as in SS-ISL.LS1

3.1.6 SS-ISL.DERT2: Steady State Islanding – DER Trip (Generation < Demand)

The test verifies if the microgrid can handle the loss of generation power e.g. due to a trip of DER's if there is less available generation as electricity demand. Controllable and non-controllable DER do not have enough resources to supply the load demand. For this case load-shedding or discharging of a storage unit is necessary to stay into islanded mode. Alternatively, the microgrid could switch into grid-connected mode, but this should be tested within a separate test scenario and this option not be activated within this scenario.

Table 11: Test Specification SS-ISL.DERT2

Reference to Test Case	SS-ISL
Title of Test	SS-ISL.DERT2: Steady State Islanding – DER Trip (Generation < Demand)
Specific Test System	Same as in SS-ISL.LS1
Target measures	Same as in SS-ISL.LS3
Input and output parameters	Same as in SS-ISL.DERT1
Test Design	Same as in SS-ISL.DERT1
Initial system state	<ul style="list-style-type: none"> - The system is in islanded mode - Non-grid forming DER are operating - The DER that will trip is operating at 20% of nominal power - All other generators cannot take over the generation of the DER that will trip.
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	Same as in SS-ISL.LS1
Source of uncertainty	N/A
Suspension criteria / Stopping criteria	Same as in SS-ISL.LS1

3.1.7 SS-ISL.DER_Steps: Steady State Islanding – DER Steps: Varying DER generation

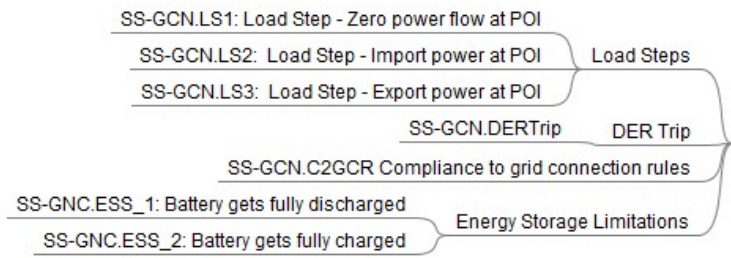
For this test the power output of controllable DER is changed and response and settling time until steady state determined.

Table 12: Test Specification SS-ISL.DER_STEPS

Reference to Test Case	SS-ISL
Title of Test	SS-ISL.DER_Steps: Steady State Islanding – DER Steps: Varying DER generation
Specific Test System	Same as in SS-ISL.LS1
Target measures	Same as in SS-ISL.LS1
Input and output parameters	Same as in SS-ISL.LS1
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in islanded mode according to “initial system state” description 2. A base load is on 3. Power output of controllable DER is changed from zero to 20% of nominal power. 4. Wait until the system reaches a steady state again <p>Repeat steps 2 to 5 in 20% power steps until nominal power is reached</p>
Initial system state	<ul style="list-style-type: none"> - The system is in islanded mode - Non-controllable DER are operating - A base load is on
Evolution of system state and test signals	Same as in SS-ISL.LS1
Other parameters	Same as in SS-ISL.LS1
Temporal resolution	Same as in SS-ISL.LS1
Source of uncertainty	Same as in SS-ISL.LS1
Suspension criteria / Stopping criteria	Same as in SS-ISL.LS1

3.2 SS-GCN: Steady State Grid Connected

Table 13: Test case description – Steady state grid connected

Name of the Test Case	SS-GCN Steady state grid connected
Narrative	<p>For the test the microgrid is operating in grid connected mode, hence the POC breaker is closed. Similar to steady state islanding, load steps and DER trips are chosen as test scenarios. One objective of the MGCS is to maintain a desired exchange power between utility grid and microgrid at the POC. Another aim is to verify if individual dispatch objectives are performed properly. The developed test scenarios for the steady state grid connected are shown in Figure 4.</p>  <p>Figure 4: Test scenarios for SS-GCN: Steady State Grid Connected</p>
Function(s) under Investigation (FuI) "the referenced specification of a function realized (operationalized) by the object under investigation"	<ul style="list-style-type: none"> - Individual dispatch functions - Desired power exchange at the POC
Object under Investigation (Oul) "the component(s) (1...n) that are to be qualified by the test"	Microgrid Control System (MGCS)
Domain under Investigation (Dul): "the relevant domains or sub-domains of test parameters and connectivity."	<ul style="list-style-type: none"> - Control algorithm - Power - Communication
Purpose of Investigation (Pol) The test purpose in terms of Characterization, Verification, or Validation	<ul style="list-style-type: none"> - Characterization of the performance – response and settling time until the desired exchange power with the utility grid is maintained after a deviation e.g. due to load or DER steps, DER trips etc. - Validation if the power is dispatched by the MGCS according to a specific strategy as reducing electricity costs etc.
System under Test (SuT): Systems, subsystems, components	Microgrid: Inverters, energy storage system, point of in-

included in the test case or test setup.	terconnection breaker, loads, generators, synchronization unit etc.
Functions under Test (FuT) Functions relevant to the operation of the system under test, including Ful and relevant interactions btw. Oul and SuT.	Droop control of generators
Test criteria: Formulation of criteria for each Pol based on properties of SuT; encompasses properties of test signals and output measures.	<ul style="list-style-type: none"> - Power at POC enters tolerance band $\pm X$ kW (defined by microgrid operator, owner etc.) - Power set points of generators, according to individual dispatch objective (e.g. set points according to price optimization, increase share of renewable generation etc.)
target metrics Measures required to quantify each identified test criteria	<ul style="list-style-type: none"> - Response time for the power adjustment at the POC - Settling time for the power adjustment at the POC
quality attributes threshold levels for test result quality as well as pass/fail criteria.	Allowable control deadband: $\pm X$ kW of desired grid exchange power.

3.2.1 SS-GCN.LS1: Steady State Grid Connected: Load steps – Zero power flow at POC

The microgrid is operating in grid-connected mode and the MGCS is parametrized that zero power between microgrid and utility grid is exchanged at the POC (within a specified tolerance around zero). After the load is switched on, the power flow at the POC may reduce until the MGCS adjusts the generation power. The settling time is defined as time until the power at the POC enters and stays within the specified tolerance band.

Table 14: Test Spec. SS-GCN.LS1: Steady State Grid Connected: Load steps – Zero power flow

Reference to Test Case	SS-GCN
Title of Test	SS-GCN.LS1: Steady State Grid Connected: Load steps – Zero power flow at POC
Specific Test System	Same as in SS-ISL.LS1
Target measures	<ol style="list-style-type: none"> 1. How long is the time until the power at the POC reaches a stable operating point (ΔP_{Set} within tolerance band defined by the involved parties or test engineer) 2. If a certain dispatch objective with concerns to the generation is required, are the power levels of DER and load as expected.
Input and output parameters	Same as in SS-ISL.LS1
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in grid connected mode according to "initial system state" description 2. Zero exchange power at the POC is set and power is within a certain tolerance band. 3. Wait until the system reaches a steady state 4. Largest load is turned on, total electricity demand is supplied by generation within the μ-grid

	5. Wait until the system reaches a steady state 6. Turn off load <i>Repeat step 4 to 6 at least three times</i>
Initial system state	<ul style="list-style-type: none"> - The system is operating in steady state grid connected mode - POC breaker is closed - Zero exchange power at the POC is set and power is within a certain tolerance band - A symmetrical base load is on (see test design) - DERs have enough reserve to supply additional load in the range of the largest load in order that zero grid exchange power can be maintained.
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	N/A
Source of uncertainty	N/A
Suspension criteria / Stop-ping criteria	<i>Expected power level at POC cannot be maintained after X minutes</i>

3.2.2 SS-GCN.LS2: Steady State Grid Connected: Load steps – Import power at POC

The microgrid is operating in grid-connected mode and the MGCS is parametrized that power is imported from the utility grid. A load is switched on and the MGCS is required to adapt the generation power to maintain the desired import power at the POC. The settling time until the power at the POC enters and stays within the specified tolerance band is determined.

Table 15: Test Spec. SS-GCN.LS2: Steady State Grid Connected: Load steps – Import power at POC

Reference to Test Case	SS-GCN
Title of Test	SS-GCN.LS2: Steady State Grid Connected: Load steps – Import power at POC
Specific Test System	Same as in SS-ISL.LS1
Target measures	Same as in SS-GCN.LS1
Input and output parameters	Same as in SS-ISL.LS1
Test Design	1. Microgrid is operating in grid connected mode according to “initial system state” description 2. A power exchange from the utility grid to the microgrid is set at the POC. 3. Wait until the system reaches a steady state 4. Largest load is turned on 5. Wait until the system reaches a steady state 6. Turn off load <i>Repeat step 4 to 6 at least three times</i>
Initial system state	<ul style="list-style-type: none"> - The system is operating in steady state grid connected mode - POC breaker is closed - A power exchange (import power) from the utility grid to the microgrid is set at the POC. - A symmetrical base load is on (see test design) - DERs have enough reserve to supply additional load in the range of the largest load in order that the desired grid exchange power can be maintained.

Evolution of system state and test signals	N/A
Other parameters	N/A
Other parameters	N/A
Temporal resolution	N/A
Source of uncertainty	N/A
Suspension criteria / Stop-ping criteria	Same as in SS-GCN.LS1

3.2.3 SS-GCN.LS3: Steady State Grid Connected: Load steps – Export power at POC

The microgrid is operating in grid-connected mode and the MGCS is parametrized that power is exported from the microgrid to the utility grid. A load is turned on and after the load step the power flow at the POC may be reduced. The MGCS is required to increase the generation to maintain the desired export power at the POC. The settling time until the power at the POC enters and stays within the specified tolerance band around the desired power exchange is determined.

Table 16: Test Spec. SS-GCN.LS3 Steady State Grid Connected: Load steps – Export power at POC

Reference to Test Case	SS-GCN
Title of Test	SS-GCN.LS3: Steady State Grid Connected: Load steps – Export power at POC
Specific Test System	Same as in SS-ISL.LS1
Target measures	Same as in SS-GCN.LS1
Input and output parameters	Same as in SS-ISL.LS1
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in grid connected mode according to “initial system state” description 2. A power exchange (export power) from the microgrid to the utility is set at the POC. 3. Wait until the system reaches a steady state 4. Largest load is turned on, total electricity demand is supplied by generation within the μ-grid 5. Wait until the system reaches a steady state 6. Turn off load <p>Repeat step 4 to 6 at least three times</p>
Initial system state	<ul style="list-style-type: none"> - The system is operating in steady state grid connected mode - POC breaker is closed - A power exchange from the microgrid to the utility is set at the POC - A symmetrical base load is on (see test design) - DERs have enough reserve to supply additional load in the range of the largest load in order that the desired grid exchange power can be maintained.
Evolution of system state and test signals	N/A
Other parameters	N/A
Other parameters	N/A
Temporal resolution	N/A
Source of uncertainty	N/A
Suspension criteria / Stop-ping criteria	Same as in SS-GCN.LS1

3.2.4 SS-GCN.DER Trip

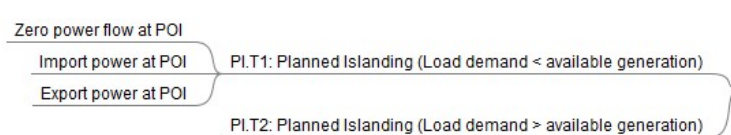
For this test a DER is tripped. At the POC zero exchange power with the utility grid is set. After the DER Trip other controllable and non-controllable DER and storage units can supply the load and keep the grid exchange power zero.

Table 17: Test Specification SS-GCN.DER Trip

Reference to Test Case	SS-GCN
Title of Test	<i>DER-Trip</i>
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<i>Same as in SS-SS-GCN.LS1</i>
Input and output parameters	<i>Same as in SS-SS-GCN.LS1</i>
Test Design	<ol style="list-style-type: none"> 1. Microgrid is operating in grid connected mode according to "initial system state" description 2. Zero grid exchange power at the POC is set and power is within a certain tolerance band 3. Wait until the system reaches a steady state 4. Base load of the μ-grid is turned on – DER supply the load and have enough capacity to supply the load after the DER trip and to keep the desired power at the POC around zero within the specified tolerance band. 5. DER TRIP 6. Wait until the system reaches a steady state
Initial system state	<ul style="list-style-type: none"> - POC breaker is closed -the system is in grid connected mode - Non grid-forming DER are operating - A base load is on - Zero grid exchange power at the POC is set - DERs have enough reserve to supply the load in the range of the power of the DER to be tripped in order that zero grid exchange power can be maintained. <p><i>Note: depending on the μ-grid, DER and loads can either be single phase, symmetrical three-phase or symmetrical and un-symmetrical</i></p>
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	N/A
Source of uncertainty	N/A
Suspension criteria / Stopping criteria	<i>Same as in SS-GCN.LS1</i>

3.3 PI: Planned Islanding

Table 18: Test case description – PI: Planned Islanding

Name of the Test Case	PI: Planned Islanding
Narrative	<p>Planned islanding requires the microgrid to switch on command from grid-connected to islanded mode. Depending on the microgrid and used POC breaker, it may be required that the grid exchange power is reduced to zero before opening the POC breaker. Test scenarios are generated with different initial conditions of the grid exchange power. The test case is shown in Figure 5. One test case requires that the load is higher than the available generation within the microgrid (if possible to set). If the MGCS can shed loads or discharge a storage unit islanding should be feasible for this case.</p>  <p>Figure 5: Test scenarios for SS-PI: Planned Islanding</p>
Function(s) under Investigation (FuI) "the referenced specification of a function realized (operationalized) by the object under investigation"	<ul style="list-style-type: none"> - Planned islanding - Transition from grid-connected to islanding mode
Object under Investigation (Oul) "the component(s) (1...n) that are to be qualified by the test"	Microgrid Control System (MGCS)
Domain under Investigation (Dul): "the relevant domains or sub-domains of test parameters and connectivity."	<ul style="list-style-type: none"> - Control algorithm - Power - Communication
Purpose of Investigation (Pol) The test purpose in terms of Characterization, Verification, or Validation	<ul style="list-style-type: none"> - Validation if islanding is performed - Verification if equipment and voltage and frequency specifications are not exceeded during the transition
System under Test (SuT): Systems, subsystems, components included in the test case or test setup.	Microgrid: Inverters, energy storage system, breaker at the point of interconnection, loads, generators, synchronization unit etc.
Functions under Test (FuT) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. Oul	Functionality of secondary control and the POC circuit breaker

and SuT.		
Test criteria: Formulation of criteria for each Pol based on properties of SuT; encompasses properties of test signals and output measures.		<ul style="list-style-type: none"> - Transition from grid-connected to islanded mode succeeded - Voltage and frequency at POC within specifications during transition - Response and settling time of frequency after islanding
target metrics Measures required to quantify each identified test criteria		<ul style="list-style-type: none"> - Settling time until the microgrid frequency reaches steady state again after a planned islanding event
quality attributes threshold levels for test result quality as well as pass/fail criteria.		<ul style="list-style-type: none"> - Allowable control deadband: $\pm X$ mHz of the frequency in islanded mode.

3.3.1 PI.T1: Planned Islanding (Load demand < available generation)

The test for planned islanding is done with different grid exchange power targets. For some microgrid setups it may be required that the MGCS reduces the power at the POC to zero before islanding.

Table 19: Test Specification PI.T1: Planned Islanding (Load demand < available generation)

Reference to Test Case	<i>PI</i>
Title of Test	PI.T1: Planned Islanding (Load demand < available generation)
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<ol style="list-style-type: none"> 1. <i>Is the transition initiated and the μ-grid operating in islanded mode after the transition?</i> 2. <i>How long is the time until voltage and/or frequency reaches a stable operating point (Δf and ΔU within tolerance band defined by the involved parties or test engineer)</i> 3. <i>Is the voltage and frequency within its allowed operating range during the transition</i>
Input and output parameters	<i>Same as in SS-ISL.LS1</i>
Test Design	<ol style="list-style-type: none"> 1. <i>Microgrid is operating in grid connected mode according to "initial system state" description</i> 2. <i>Send Planned Islanding command</i>
Initial system state	<ul style="list-style-type: none"> - <i>The system operates in grid connected mode (POC breaker closed)</i> - <i>Non grid-forming DER are operating</i> - <i>A base load, which can be supplied entirely from generation of μ-grid is turned on</i> - <i>Scenarios</i> <ol style="list-style-type: none"> 1. <i>Zero grid exchange power at the POC is set</i> 2. <i>Import power at POC.</i> 3. <i>Export power at POC</i> <p><i>Note: depending on the μ-grid, DER and loads can either be single phase, three-phase symmetrical or un-symmetrical</i></p>
Evolution of system state and	<i>N/A</i>

test signals	
Other parameters	N/A
Temporal resolution	Same as in SS-ISL.LS1
Source of uncertainty	N/A
Suspension criteria / Stopping criteria	POC breaker does not open X seconds after islanding command was sent.

3.3.2 PI.T2: Planned Islanding (Load demand > available generation)

For this test the maximum generation is smaller than the load demand, before the islanding command is sent. For this case load-shedding or discharging a storage might be required in order to go into islanded mode. The test verifies if the MGCS can take actions to switch into islanded mode, even if the initial system state is in principle not suitable for islanding.

Table 20: Test Specification PI.T2: Planned Islanding (Load demand > available generation)

Reference to Test Case	PI
Title of Test	PI.T2: Planned Islanding (Load demand > available generation)
Specific Test System	Same as in SS-ISL.LS1
Target measures	<ol style="list-style-type: none"> 1. Is the μ-grid operating in islanded mode after the transition. 2. How long is the time until voltage and/or frequency reaches a stable operating point (Δf and ΔU within tolerance band defined by the involved parties or test engineer) 3. Is the voltage and frequency within its allowed operating range during the transition
Input and output parameters	Same as in SS-ISL.LS1
Test Design	Same as in PI.T1
Initial system state	<ul style="list-style-type: none"> - The system is in grid connected mode (POC breaker closed) - Non grid-forming DER are operating - A load is on, which cannot be supplied entirely from generation of μ-grid additional grid imports are necessary. <p>Note: depending on the μ-grid, DER and loads can either be single phase, three-phase symmetrical or un-symmetrical</p>
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	Same as in SS-ISL.LS1
Source of uncertainty	N/A
Suspension criteria / Stopping criteria	N/A

3.4 UPI: Unplanned Islanding

Table 21: Test case description – UPI: Unplanned Islanding

Name of the Test Case	UPI Unplanned Islanding
Narrative	<p>Unplanned islanding may be required if there is a grid outage and the microgrid shall continue its operation in islanded mode. The grid outage can be emulated in the laboratory with a grid simulator or additional circuit breaker.</p> <p>UPI.T1: Outage of the main grid (grid simulator, additional breaker)</p> <p>UPI.T2: Voltage, frequency or powerQuality of the main grid requires islanding</p> <p>Figure 6: Test scenarios for UPI: Unplanned Islanding</p>
Function(s) under Investigation (FuI) “the referenced specification of a function realized (operationalized) by the object under investigation”	<ul style="list-style-type: none"> - Unplanned islanding - Transition from grid-connected to islanding mode
Object under Investigation (Oul) “the component(s) (1...n) that are to be qualified by the test”	Microgrid Control System (MGCS)
Domain under Investigation (DuI): “the relevant domains or sub-domains of test parameters and connectivity.”	<ul style="list-style-type: none"> - Control algorithm - Power - Communication
Purpose of Investigation (Pol) The test purpose in terms of Characterization, Verification, or Validation	<ul style="list-style-type: none"> - Validation if islanding is performed in case of a grid outage, or if grid voltage / frequency of the main grid is outside the specifications. - Verification if equipment and voltage and frequency specifications in the microgrid are not exceeded during the transition. - Does the POC breaker open and “Anti-Islanding” [10] requirements of national grid codes are fulfilled?
System under Test (SuT): Systems, subsystems, components included in the test case or test setup.	Microgrid: Inverters, energy storage system, breaker at the point of interconnection, loads, generators, synchronization unit etc.
Functions under Test (FuT) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. Oul and SuT.	Functionality of the POC circuit breaker
Test criteria: Formulation of criteria for each Pol based on properties of	<ul style="list-style-type: none"> - Response and settling time until the frequency reaches steady state after islanding

SuT; encompasses properties of test signals and output measures.	- Voltage and frequency at POC within the specifications during transition
target metrics Measures required to quantify each identified test criteria	- Settling time until the microgrid frequency reaches steady state after unplanned islanding
quality attributes threshold levels for test result quality as well as pass/fail criteria.	- Allowable control deadband: $\pm X$ mHz of the frequency in islanded mode.

3.4.1 UPI.T1: Outage of the main grid

Table 22: Test Specification UPI.T1

Reference to Test Case	<i>UPI</i>
Title of Test	<i>UPI.T1: Outage of the main grid</i>
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<ol style="list-style-type: none"> <i>1. Is the μ-grid forming an islanded grid</i> <i>2. Does the POC breaker opens automatically ("Anti Islanding" functionality of national grid codes)?</i> <i>3. Is the voltage and frequency in the microgrid within its allowed operating range during the transition</i> <i>4. Is the secondary control working?</i> <i>5. How long is the time until voltage and/or frequency reaches a stable operating point (Δf and ΔU within tolerance band defined by the involved parties or test engineer)</i>
Input and output parameters	<i>Same as in UPI.T1</i>
Test Design	<ol style="list-style-type: none"> <i>1. Microgrid is operating in grid connected mode according to "initial system state" description</i> <i>2. Grid simulator is turned off or a for the test dedicated breaker is used.</i>
Initial system state	<ul style="list-style-type: none"> <i>- The system is in grid connected mode (POC breaker closed)</i> <i>- A grid simulator is used to form the grid or a dedicated breaker additionally to the POC breaker of the microgrid is used to disconnect from the grid.</i> <i>- Non grid forming DER are operating</i> <i>- A base load, which can be supplied entirely from generation of the μ-grid is turned on</i> <p><i>Note: depending on the μ-grid, DER and loads can either be single phase, three-phase symmetrical or un-symmetrical</i></p>
Evolution of system state and test signals	<i>N/A</i>
Other parameters	<i>N/A</i>
Temporal resolution	<i>N/A</i>
Source of uncertainty	<i>N/A</i>
Suspension criteria / Stopping criteria	<i>N/A</i>

3.4.2 UPI.T2: Voltage, frequency or power quality of the main grid requires islanding

Table 23: PI.T2: Voltage, frequency or power quality of the main grid requires islanding

Reference to Test Case	<i>UPI</i>
Title of Test	<i>UPI.T2: Voltage, frequency or power quality of the main grid requires islanding</i>
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<i>Same as in UPI.T1</i>
Input and output parameters	<i>Same as in SS-ISL.LS1</i>
Test Design	<ol style="list-style-type: none"> 1. Microgrid operates in grid-connected mode according to "initial system state" description 2. Voltage, frequency or power quality is changed with a grid simulator in order that islanding will be necessary (e.g. due to over/under voltage/frequency of the utility grid).
Initial system state	<i>Same as in UPI.T1</i>
Evolution of system state and test signals	<i>N/A</i>
Other parameters	<i>N/A</i>
Temporal resolution	<i>N/A</i>
Source of uncertainty	<i>N/A</i>
Suspension criteria / Stop-ping criteria	<i>N/A</i>

3.5 RC: Reconnection

Table 24: Test case description – RC Reconnection

Name of the Test Case	RC Reconnection
Narrative	<p><i>The test verifies if the system reconnects from islanded to grid-connected mode after a reconnection signal is sent or if the islanded mode cannot be maintained anymore e.g. due to an unbalance between generation and demand. For the reconnection a synchronization between both grids is necessary. The POC breaker is not allowed to switch before frequency and phase angle of the utility grid and microgrid matches the reconnection criteria.</i></p> <p>RC.T1: Reconnection signal sent (Reconnection allowed)</p> <p>RC.T2: Reconnection signal sent (Reconnection not allowed)</p> <p>RC.T2: Automatically reconnect due to critical microgrid situations e.g. loss of DER</p> <p><i>Figure 7: Test scenarios for the Reconnection test case</i></p>
Function(s) under Investigation (FuI) "the referenced specification of a function realized (operationalized) by the object under investigation"	<ul style="list-style-type: none"> - Reconnection - Transition from islanded to grid-connected mode
Object under Investigation (OuI) "the component(s) (1...n) that are to be qualified by the test"	Microgrid Control System (MGCS)

Domain under Investigation (DuI): “the relevant domains or sub-domains of test parameters and connectivity.”	<ul style="list-style-type: none"> - Control algorithm - Power - Communication
Purpose of Investigation (PoI) The test purpose in terms of Characterization, Verification, or Validation	<ul style="list-style-type: none"> - Validation if the microgrid reconnects to the utility grid after the reconnection signal is sent
System under Test (SuT): Systems, subsystems, components included in the test case or test setup.	Microgrid: Inverters, energy storage system, point of interconnection breaker, Loads, Generators, Synchronization unit etc.
Functions under Test (FuT) Functions relevant to the operation of the system under test, including Ful and relevant interactions btw. Oul and SuT.	<ul style="list-style-type: none"> - Synchronization
Test criteria: Formulation of criteria for each PoI based on properties of SuT; encompasses properties of test signals and output measures.	<ul style="list-style-type: none"> - Did the POC breaker close and reconnection to the utility grid is established?
target metrics Measures required to quantify each identified test criteria	<ul style="list-style-type: none"> - POC breaker closed, utility grid and microgrid frequency are the same
quality attributes threshold levels for test result quality as well as pass/fail criteria.	<ul style="list-style-type: none"> - Allowable control deadband: $\pm X$ kW of desired grid exchange power.

3.5.1 RC.T1: Reconnection signal sent (Reconnection allowed)

A reconnection request is sent to the MGCS and the transition from island to grid-connected mode examined.

Table 25: RC.T1: Reconnection signal sent (Reconnection allowed)

Reference to Test Case	<i>RC</i>
Title of Test	RC.T1: Reconnection signal sent (Reconnection allowed)
Specific Test System	<i>Same as in SS-ISL.LS1</i>
Target measures	<ol style="list-style-type: none"> 1. <i>Did the POC breaker close and reconnection established?</i> 2. <i>Is the voltage and frequency within its limitations during the transition</i>
Input and output parameters	<i>Same as in SS-ISL.LS1</i>
Test Design	<ol style="list-style-type: none"> 1. <i>Microgrid is operating in islanded mode, according to “initial system state” description</i> 2. <i>Reconnection request signal is sent</i>
Initial system state / Initial conditions	<ul style="list-style-type: none"> - <i>POC breaker is open. The system operates in steady state island mode</i>

	<ul style="list-style-type: none"> - A base load is on - Frequency/voltage of the main grid is within its specifications
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	N/A
Source of uncertainty	N/A
Suspension criteria / Stopping criteria	N/A

3.5.2 RC.T2: Reconnection signal sent (Reconnection not allowed)

In this case a reconnection is not allowed because the voltage/frequency of the main grid is out of specification e.g. due to a blackout.

Table 26: RC.T2: Reconnection signal sent (Reconnection allowed)

Reference to Test Case	RC
Title of Test	RC.T2: Reconnection signal sent (Reconnection not allowed)
Specific Test System	Same as in SS-ISL.LS1
Target measures	Did the POC breaker close and a reconnection was possible even if it was not allowed?
Input and output parameters	Same as in SS-ISL.LS1
Test Design	Same as in RC.T1
Initial system state / Initial conditions	POC breaker is open. The system operates in steady state island mode <ul style="list-style-type: none"> - A base load is on - Frequency/voltage of the main grid is slightly out of the reconnection specifications Note: a reconnection in this case could be a critical issue and destroy components
Evolution of system state and test signals	N/A
Other parameters	N/A
Temporal resolution	N/A
Source of uncertainty	N/A
Suspension criteria / Stopping criteria	N/A

3.5.3 RC.T3. Automatically reconnect due to critical microgrid situations e.g. loss of DER

The microgrid may reconnect automatically to the utility grid if otherwise it is not able to provide stable operation in island mode anymore e.g. due to a loss of DER and not enough generation power within the microgrid and no other options as load-shedding are available. This test may be part of other scenarios if foreseen e.g. SS-ISL.DERT2: DER Trip (Generation < Demand)

Table 27: Test Specification RC.T3: automatically reconnect due to critical microgrid situations

Reference to Test Case	RC
Title of Test	RC.T3 Automatically reconnect due to critical microgrid situations e.g. loss of DER
Specific Test System	Same as in SS-ISL.LS1
Target measures	Did the microgrid shuts down or reconnects to the utility grid?

Input and output parameters	<i>Same as in SS-ISL.LS1</i>
Test Design	<ol style="list-style-type: none"> <i>1. Microgrid operates in island mode, according to “initial system state” description</i> <i>2. An event is produced in which the microgrid cannot operate itself anymore and needs to reconnect to the main grid.</i>
Initial system state / Initial conditions	<ul style="list-style-type: none"> <i>- The system operates in steady state islanding mode – POC breaker is open</i> <i>- A base load is on</i>
Evolution of system state and test signals	<i>N/A</i>
Other parameters	<i>N/A</i>
Temporal resolution	<i>N/A</i>
Source of uncertainty	<i>N/A</i>
Suspension criteria / Stopping criteria	<i>N/A</i>

4 Executed Tests and Experiments

In this chapter the microgrid setup is described, followed by *experiment specifications* (according to the holistic test specification templates) and the results of tests.

4.1 Microgrid test setup

The microgrid test setup at TECNALIA is shown in Figure 8. Two 40 kW inverters, which can operate grid forming and grid following mode, are used. They are fed by a DC source and connected over a delta-star transformer to the grid. Due to those transformers unbalanced operation is possible. A 40 kW three phase load bank is available. A POC breaker in combination with a synchro-relay is used for connecting the microgrid with the utility grid or a grid simulator. The synchro relay is required to verify the phase angle and frequency difference between microgrid and main grid for the reconnection from islanded to grid-connected mode.

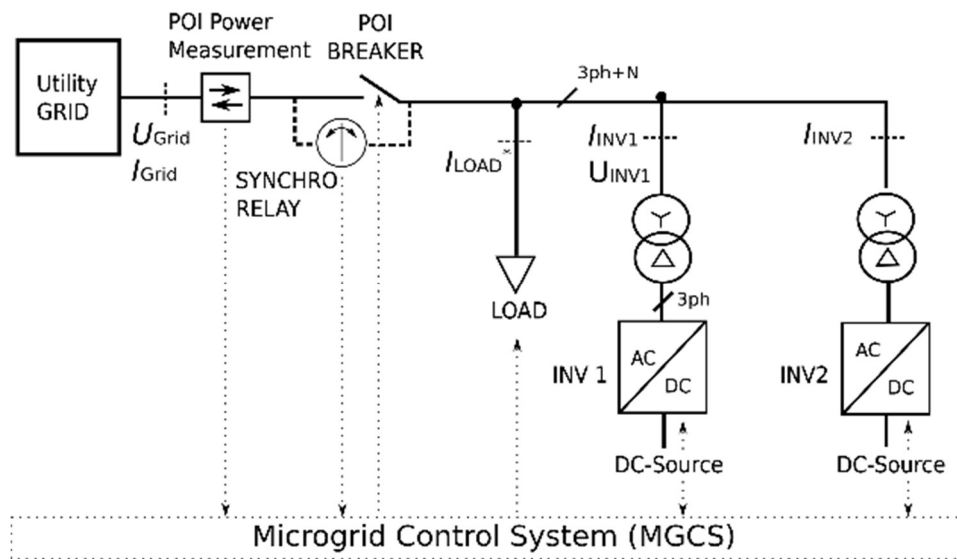


Figure 8: TECNALIA's Microgrid Laboratory Setup including measurement points (dashed lines)

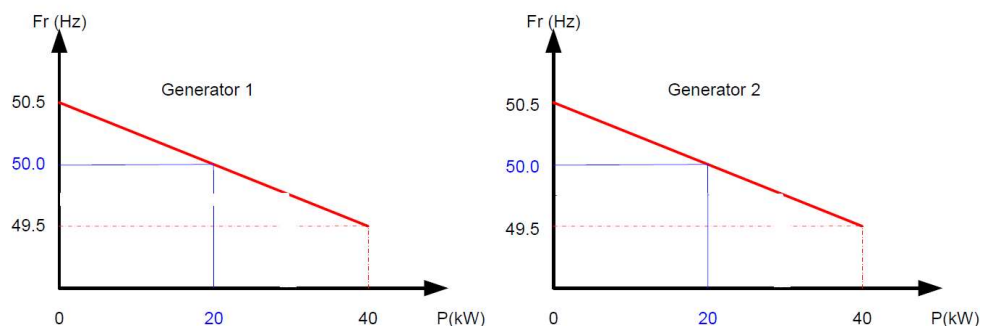
Due to various reasons, e.g. other projects at the same time at the host institute, not all devices (grid tied PV inverter/storage system) were available. On the other side, a Regatron ACS was available for a part of the project. This device was used both as a grid simulator and as RLC load. A setup table following the holistic test specification is given in Table 28.

Table 28: Experiment setup at TECNALIA

Research Infrastructure	<i>TECNALIA Microgrid Laboratory</i>
Experiment Realization	<i>Microgrid Hardware Setup</i>
Experiment Setup (concrete lab equipment)	<ul style="list-style-type: none"> - TECNALIA Microgrid Control System - Generator 1: Inverter 40 kW with droop control - Generator 2: Inverter 40 kW with droop control - Symmetrical Load Cascade <ul style="list-style-type: none"> • Load 1: 1.39 kW • Load 2: 2.78 kW • Load 3: 5.56 kW • Load 4: 11.1 kW • Load 5: 16.6 kW - Synchro Relay - Power Breaker at POC - Dewesoft Sirius measurement system
Storage of data	<i>Dewesoft DATA File</i>

4.1.1 Primary control

The primary control implemented in the two microgrid forming inverters consist of a P/f and a V/Q droop control. The active and reactive power output is controlled according to specified droop curves as function of the measured voltage and frequency. The default parametrization of the droop curves is given in Figure 9, Table 29 and Table 30. After changes of the demand or generation of uncontrollable DER and hence altered power output of the grid forming inverters, they also change their frequency. Additionally, the primary control is the key control for the transition functions from grid-connected to islanded mode and vice versa.

**Figure 9: Primary control – Droop curves****Table 29: Parameter of the primary P/f control**

Frequency	Active power
50.5 Hz	0 kW
49.5 Hz	40 kW

Table 30: Parameter of the primary V/Q control

Voltage	Reactive power
437.8 V	20 kVA
358.2 V	-20 kVA

4.1.2 Secondary control

The secondary control relates to the actual microgrid energy management system and performs following actions:

- Real time visualization of data (P/Q/ F_r /V)
- Historical data storage
- Setting of predefined power schedules for DER
- Setting droop characteristics of primary control to restore the nominal grid frequency

The dispatch objective is a real time economic operation:

1. Each controllable device provides its operating costs (generation costs, electricity price, DSM strategies etc.)
2. Supply and demand are matched and a microgrid price is obtained
3. Each device is assigned a power set point according to the microgrid price

Other functions of the secondary control are:

1. Grid connected operation:
 - a. Maintains the power exchange with the main grid to predefined values
 - b. Electricity costs of the main grid can be represented as generator/load electricity prices
2. Island operation:
 - a. Recovers the reference frequency 50 Hz after deviations

Bidding strategies

The secondary controller uses the costs of each device to control the optimal power distribution of the generators, grid import/exports and to dispatch uncritical loads if necessary. The marginal cost for each device can be parametrized in the secondary control.

Three bidding strategies were used for the tests, the parametrization is shown in Table 31:

- Reference 1: Both inverters share the load, almost equally
- Reference 2: Inverter 2 always generates 10 kW (or less), Inverter 1 takes over everything above 10 kW consumption
- Reference 3: Power from the grid is imported for load consumption above 25 kW. A load dispatch of 11 kW can be done in in islanded mode when the price is too high.

Table 31: Parametrization of the bidding strategies.**Reference 1**

Bidder Agent GUI Diesel#1-Controller

Cost	Power	Indivisibility
2	1000	false
7	1000	false
12	1000	false
17	2000	false
22	5000	false
27	5000	false
32	5000	false
37	5000	false

Add Row
Remove Rows
Remove Bid
Submit Bid

Bidder Agent GUI Diesel#2-Controller

Cost	Power	Indivisibility
0	1000	false
5	1000	false
10	1000	false
15	2000	false
20	5000	false
25	5000	false
30	5000	false
35	5000	false
40	5000	false
45	5000	false

Add Row
Remove Rows
Remove Bid
Submit Bid

Bidder Agent GUI PCC-Controller

Cost	Power	Indivisibility
24.99	-200000	false
25.00	0	true
25.01	200000	false

Add Row
Remove Rows

Bidder Agent GUI AvtronK595-Load_04

Cost	Power	Indivisibility
0	-2780	true
30	0	true

Add Row
Remove Rows

Reference 2

Bidder Agent GUI PCC-Controller

Cost	Power	Indivisibility
24.99	-200000	false
25.00	0	true
25.01	200000	false

Add Row
Remove Rows
Remove Bid
Submit Bid

Bidder Agent GUI AvtronK595-Load_04

Cost	Power	Indivisibility
0	-2780	true
30	0	true

Add Row
Remove Rows
Remove Bid

Bidder Agent GUI Diesel#2-Controller

Cost	Power	Indivisibility
0	1000	false
5	1000	false
10	1000	false
15	2000	false
20	5000	false
25	5000	false
30	5000	false
35	5000	false
40	5000	false
45	5000	false

Add Row
Remove Rows
Remove Bid
Submit Bid

Bidder Agent GUI Diesel#1-Controller

Cost	Power	Indivisibility
2	1000	false
7	1000	false
12	1000	false
17	2000	false
22	5000	false
27	5000	false
32	5000	false
37	5000	false

Add Row
Remove Rows
Remove Bid
Submit Bid

Reference 3 Load Dispatch

Bidder Agent GUI AvtronK595-Load_06

Cost	Power	Indivisibility
0	-11110	true
30	0	true

Add Row
Remove Rows
Remove Bid
Submit Bid

4.2 Experiments and Results

According to the test specifications, experiment specifications for the specific microgrid test setup at TECNALIA have been generated. Not all tests from the created test specifications were applicable due to limitations of the test setup e.g. no storage system was available. Table 32 (which is basically a copy of Table 4) shows the conducted experiments highlighted in green. Tests which were not performed are marked red.

Table 32: Conducted experiments for the five IEEE 2030.8 test scenarios (ar. = arbitrary) [1]

Test case	Initiating Event	Initial Conditions			Metrics	
	/	$P_{Load, Base}$	P_{POC}	Available Gen. \geq Demand	Response, settling time (t_r , t_s) for:	Qualitative metrics
Steady-state Islanding	Largest Load Step - 3 phase symmetrical	✓	0	✓	Frequency (f)	Steady state values, dispatch objectives within contractual requirements and equipment limitations not exceeded
	Largest Load Step - unsymmetrical	✓	0	✓	f	
	Largest Load Step - symmetrical or unsymmetrical	✓	0	✗	f	
	Largest reactive load - inductive and capacitive	✓	0	✓	Voltage (U)	
	Trip of large DER	✓	0	✓	f	
	Trip of large DER	✓	0	✗	f	
	DER Steps - Change of DER output power	✓	0	✓	f	
	Energy Storage Limitations – Fully charged storage	✓	0	✓	f	
	Energy Storage Limitations – Fully discharged storage	✓	0	✓	f	
Steady-state grid-connected	Largest Load Step - symmetrical or unsymmetrical	✓	0	✓	Power at POC (P_{POC})	Steady-state values, dispatch objectives within contractual requirements and equipment limitations not exceeded
	Largest Load Step - symmetrical or unsymmetrical	✓	-	✓	P_{POC}	
	Largest Load Step - symmetrical or unsymmetrical	✓	+	✓	P_{POC}	
	Trip of large DER	✓	0	✓	P_{POC}	
	Energy Storage Limitations – Fully charged storage	✓	0	✓	P_{POC}	
	Energy Storage Limitations – Fully discharged storage	✓	0	✓	P_{POC}	
	Compliance to national grid connection rules / initial conditions as required by the specific technical rules	according to standard			-	
Planned Islanding	Planned islanding signal is sent	✓	0	✓	f	Frequency / voltage and equipment limitations not exceeded during transition
	Planned islanding signal is sent	✓	+	✓	f	
	Planned islanding signal is sent	✓	-	✓	f	
	Planned islanding signal is sent	✓	ar.	✗	f	
Un-planned Islanding	Outage of the main grid (by use of an AC simulator of dedicated POC breaker)	✓	ar.	✓	f	Is a microgrid formed
	Automatic transition to island mode is required due to a critical utility grid situation (f, U, power quality, etc.)	✓	ar.	✓	f	Does the POC breaker open?
Reconnection	Reconnection signal sent	✓	ar.	✓	P_{POC}	Time to reconnect
	Automatically reconnect due to critical islanded microgrid situation (f, U, power quality, etc.)	✓	ar.	ar.	P_{POC}	

The variables and abbreviations for the measurement plots are described below the figures as well as in Table 2.

4.2.1 SS-ISL: Steady State Islanding

4.2.1.1 SS-ISL.LS1: Largest load Step – 3 phase symmetrical

Table 33: Experiment specification SS-ISL.LS1

Title	Largest Load Step – 3 phase symmetrical
Ref. Test Specification	SS-ISL.LS1
Initial Condition	<ol style="list-style-type: none"> 1. Power Breaker at POC: Open 2. Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) Secondary Control: activated
Initiating Event	<ol style="list-style-type: none"> 1. Turn on largest load 5: 16.6 kW 2. Wait until steady state is reached or abort after X seconds if steady state is not reached or microgrid forming generator trips. 3. Turn off largest load <p>Repeat step 1 to 3 three times. Repeat test with other bidding strategies</p>
Expected insights	<ul style="list-style-type: none"> - Is the microgrid able to supply the load and to continue its operation in islanded mode? - Does frequency and voltage stay in the desired bandwidth. - Does the dispatch objective is maintained according to the bidding strategy "Reduction of the electricity price depending on the marginal generation costs"
Metrics	Settling time t_s as time between the load step and reentry of frequency into the chosen tolerance band 50 Hz \pm 0.01 Hz.
Pass / Fail criteria	<p>Pass:</p> <ul style="list-style-type: none"> - Settling time for frequency recovery would be smaller or equal as declared value (if given from the manufacturer, contractual requirements etc. // TECNALIA did not specify a settling time to achieve for the experimental platform) <p>Failure</p> <ul style="list-style-type: none"> - Minor failure: No reentry of frequency into tolerance band - Major failure: Microgrid stops operation

Bidding strategy Reference 1:

Figure 10 shows four load steps in steady state islanded mode (2 increasing, 2 decreasing steps). Bidding strategy "Reference 1" (see chapter 0) is set. After the load steps both generators immediately increase their power equally to supply the additional load demand. The frequency deviates after the load step from 50 Hz. It requires some seconds until the secondary control updates the power set points of the inverters accordingly to the bidding strategy and brings the frequency back to 50 Hz \pm 0.01 Hz. The measurement results are given in Table 34.

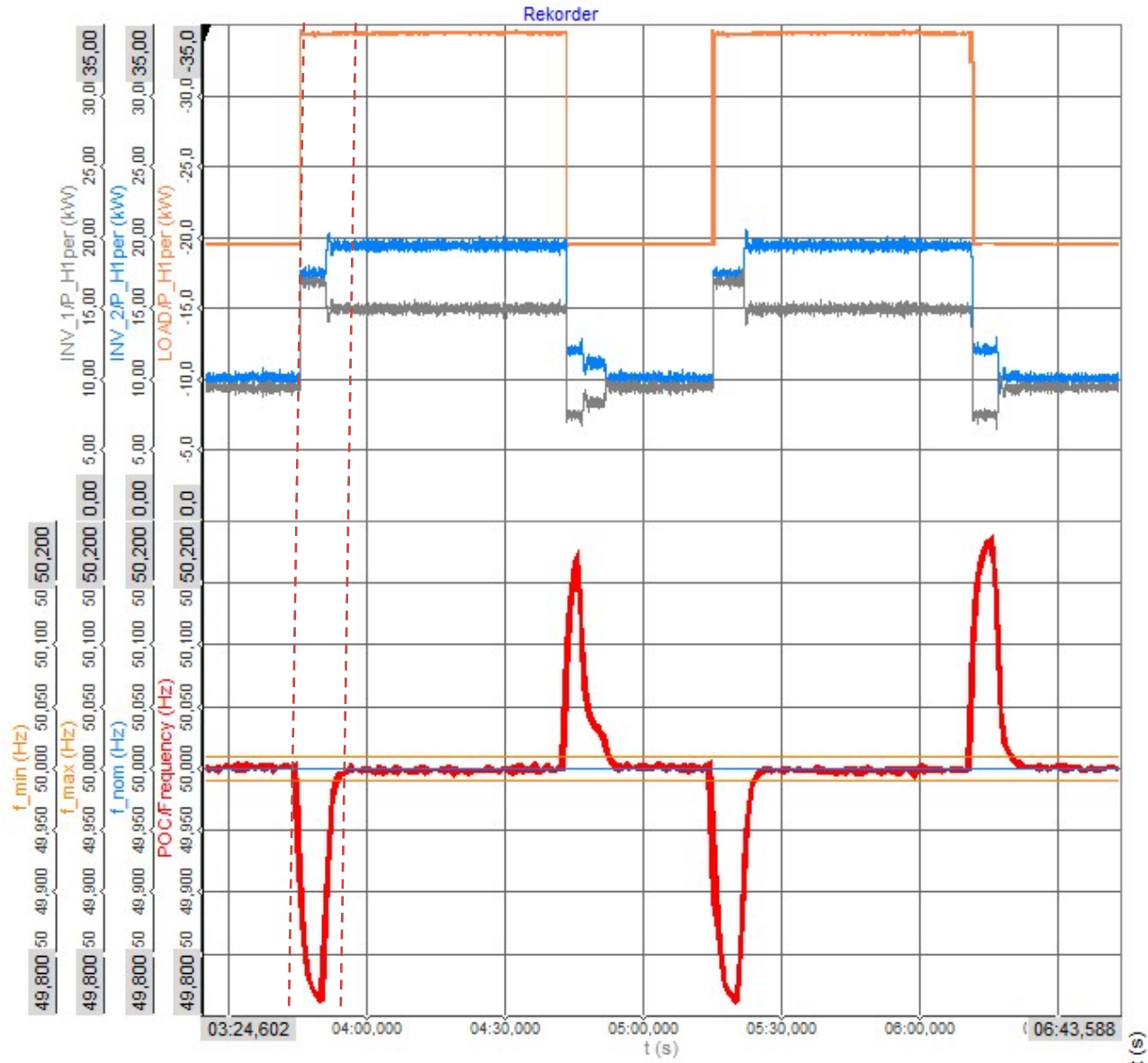


Figure 10: Steady State Islanding – Largest Load Step: Bidding Strategy Reference 1.

The vertical cursors show the time after the frequency deviation until the re-entry into the tolerance band for the first step. LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; f_nom - nominal frequency; f_min/max: 10 mHz tolerance band; (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

Table 34: Steady State Islanding – Largest Load Step: Bidding Strategy Reference 1.

		Step 1	Step 2	Step 3	Step 4
$P_{LOAD,start}$	kW	19.5	34.4	19.5	34.4
$P_{LOAD,end}$	kW	34.4	19.6	34.4	19.6
ΔP_{LOAD}	kW	14.9	-14.8	14.9	-14.8
$P_{inv\ 1,droop}$	kW	16.9	8.7	16.4	7.5
$P_{inv\ 2,droop}$	kW	17.6	10.9	17.8	11.9
$P_{inv\ 1,settled}$	kW	19.2	9.4	15.0	9.2
$P_{inv\ 2,settled}$	kW	15.2	10.1	19.4	10.2
$f_{max/min}$	Hz	49.81	50.18	49.82	50.18
$f_{delta,max,Step}$	Hz	0.19	0.18	0.19	0.18
$U_{settled\ 10s\ avg}$	V	222.0	224.6	222.9	227.9
$U_{max,Step\ 10s,avg}$	V	226.6	228.7	226.5	225.3
$U_{min,Step\ 10s,avg}$	V	218.7	224.63	220.0	222.2
t_d	s	5.5	3	6.3	5.1
t_s	s	8.5	9.5	9.2	9.1

Bidding strategy Reference 2:

Figure 11 shows the test with bidding strategy “Reference 2”. A comparison between both bidding schemes is given in Table 35 for the rising and falling load steps. The dead and settling time matches for both bidding schemes. After the secondary control starts operation the power is set accordingly to the marginal cost of the bidding scheme. inverter 2 produces around 10 kW, the rest of the load demand is supplied by inverter 1.

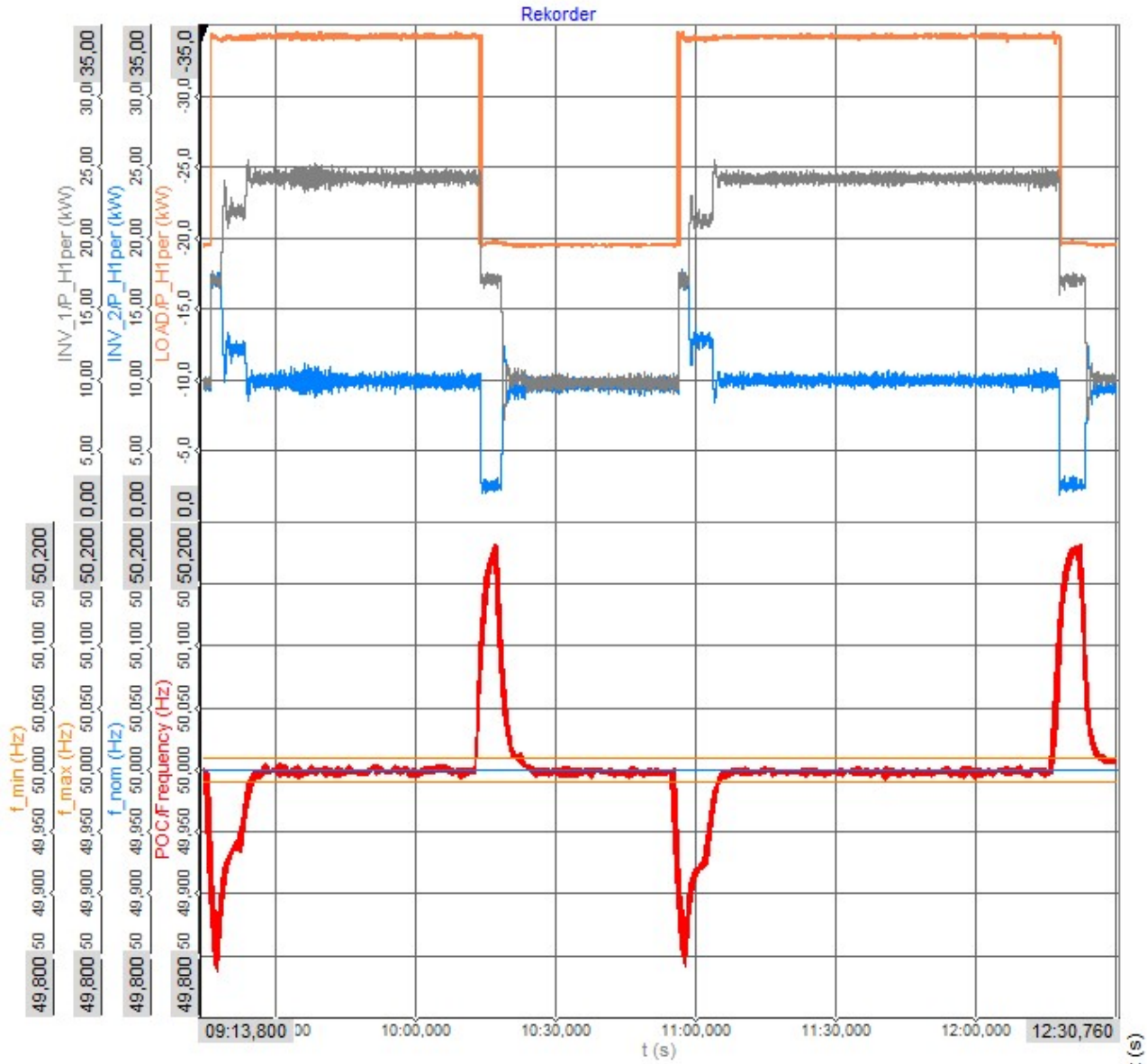


Figure 11: Steady State Islanding – Largest Load Step – Bidding Strategy 2.

$LOAD/P_per$: load power; INV_1/P_H1per , INV_2/P_H1per : active power of the first and second inverter;
 POC/F frequency: microgrid frequency; f_nom - nominal frequency; f_min/max : 10 mHz tolerance band
 (P_per : one period RMS; P_H1per : fundamental component of one period RMS)

Table 35: Comparison SS_ISL_LS1: Bidding strategy 1 and 2

	Unit	Bidding strategy 2		Bidding strategy 1	
	-	Step 1	Step 2	Step 3	Step 4
P_{LOAD,start}	kW	19.5	34.2	19.5	34.4
P_{LOAD,end}	kW	34.2	19.7	34.4	19.6
ΔP_{LOAD}	kW	14.7	-14.5	14.9	-14.8
P_{inv 1,droop}	kW	16.99	17.39	16.4	7.5
P_{inv 2,droop}	kW	16.99	2.33	17.8	11.9
P_{inv 1,settled}	kW	24.26	9.54	15.0	9.2
P_{inv 2,settled}	kW	9.94	9.99	19.4	10.2
f_{max/min}	Hz	49.84	50.182	49.82	50.18
f_{delta,max,Step}	Hz	0.163	50.178	0.19	0.18
U_{settled 10s avg}	V	218.8	224.11	222.9	227.9
U_{max,Step 10s,avg}	V	226.31	223.39	226.5	225.3
U_{min,Step 10s,avg}	V	223.87	220.59	220.0	222.2
t_d	s	2.5	4.25	6.3	5.1
t_s	s	9.5	9.5	9.2	9.1

Load shedding:

The secondary control is parametrized that in total 10 kW of the load can be shed if the marginal electricity costs are over a certain value. The test is shown in Figure 12. The load step causes a power change of both inverters accordingly to the primary droop control and after some seconds delay the secondary control updates the set points and the loads are sequentially shed (1.3 kW, 2.4 kW, 4.8 kW). At the end, the frequency is recovered, and the island operates at 50 Hz.

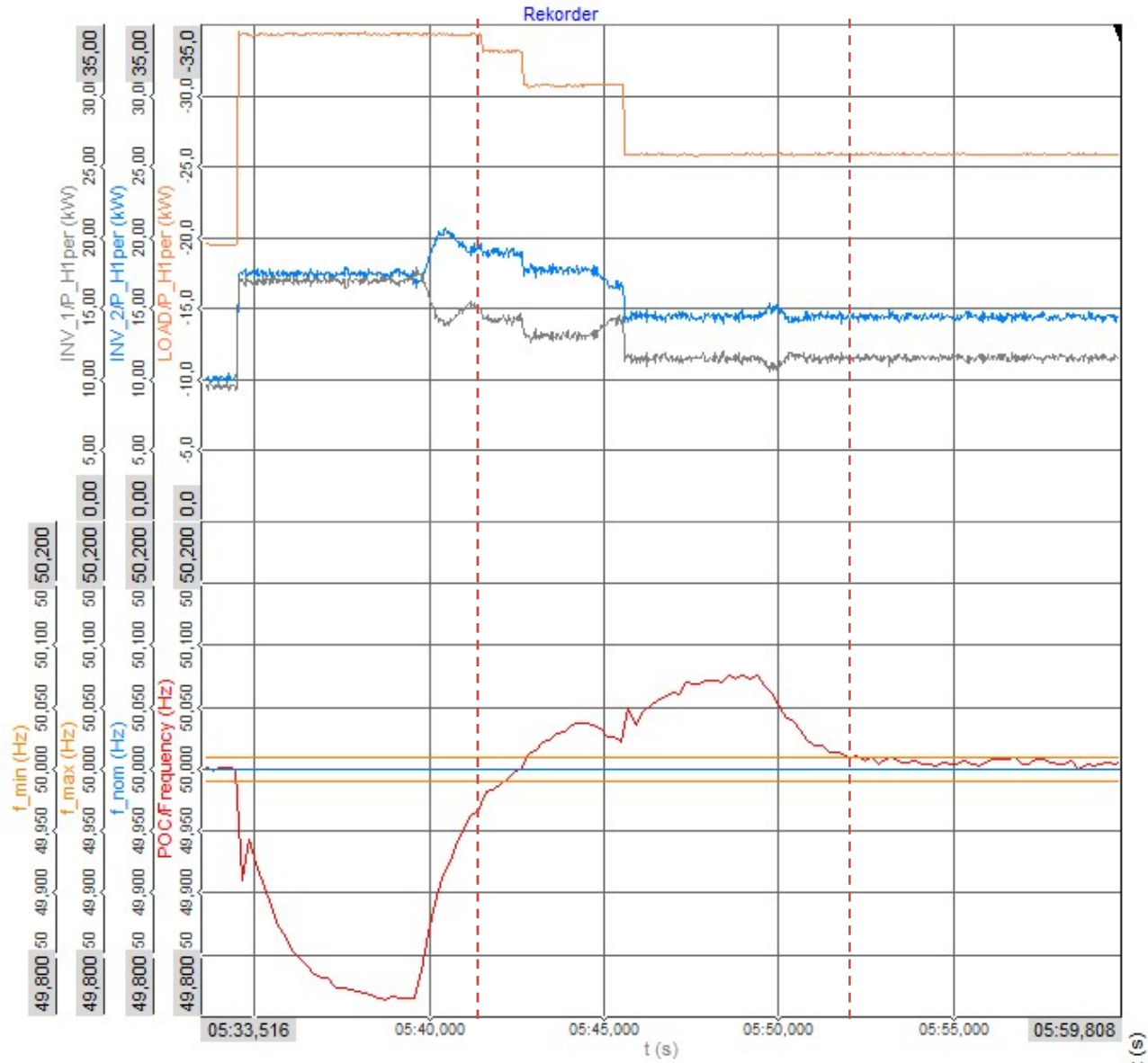


Figure 12: SS_ISL_LS1: Load shedding

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter;
POC/Frequency: microgrid frequency; f_nom - nominal frequency; f_min/max: 10 mHz tolerance band;
(P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

Table 36: SS_ISL_LS1: Load shedding

Step	Process	Time
1	Delay time t_d until the secondary control gets activated	5.3 s
2	Load shed 1.3 kW	7.0 s
3	Load shed 2.5 kW	8.1 s
4	Load shed 4.8 kW	11.0 s
5	Settling time t_s until the frequency is recovered	18.2 s

4.2.1.2 SS-ISL.LS2: Largest load Step – 3 phase unsymmetrical

Table 37: Experiment specification SS-ISL.LS2

Title	<i>Largest Load Step – 3 phase unsymmetrical</i>
Ref. Test Specification	<i>SS-ISL.LS2</i>
Initial Condition	Same as for experiment specification SS-ISL.LS1 but <i>resistive load of one phase is disconnected</i>
Initiating Event	<ol style="list-style-type: none"> 1. <i>Turn on largest load 5: 16.6 kW</i> 2. <i>Wait until steady state is reached or abort after X seconds if steady state is not reached or microgrid forming generator trips.</i> 3. <i>Turn off largest load</i> <p><i>Repeat step 1 to 3 three times.</i> <i>Repeat test with other bidding strategies</i></p>
Expected insights	Same as for experiment specification SS-ISL.LS1
Metrics	Same as for experiment specification SS-ISL.LS1
Pass / Fail criteria	Same as for experiment specification SS-ISL.LS1

Results:

Figure 13 shows the test for load steps with an unsymmetrical load. Only a load on phase one and phase two is activated. The inverters supply the unsymmetrical load and the secondary control recovers the frequency to 50 Hz after the load step.

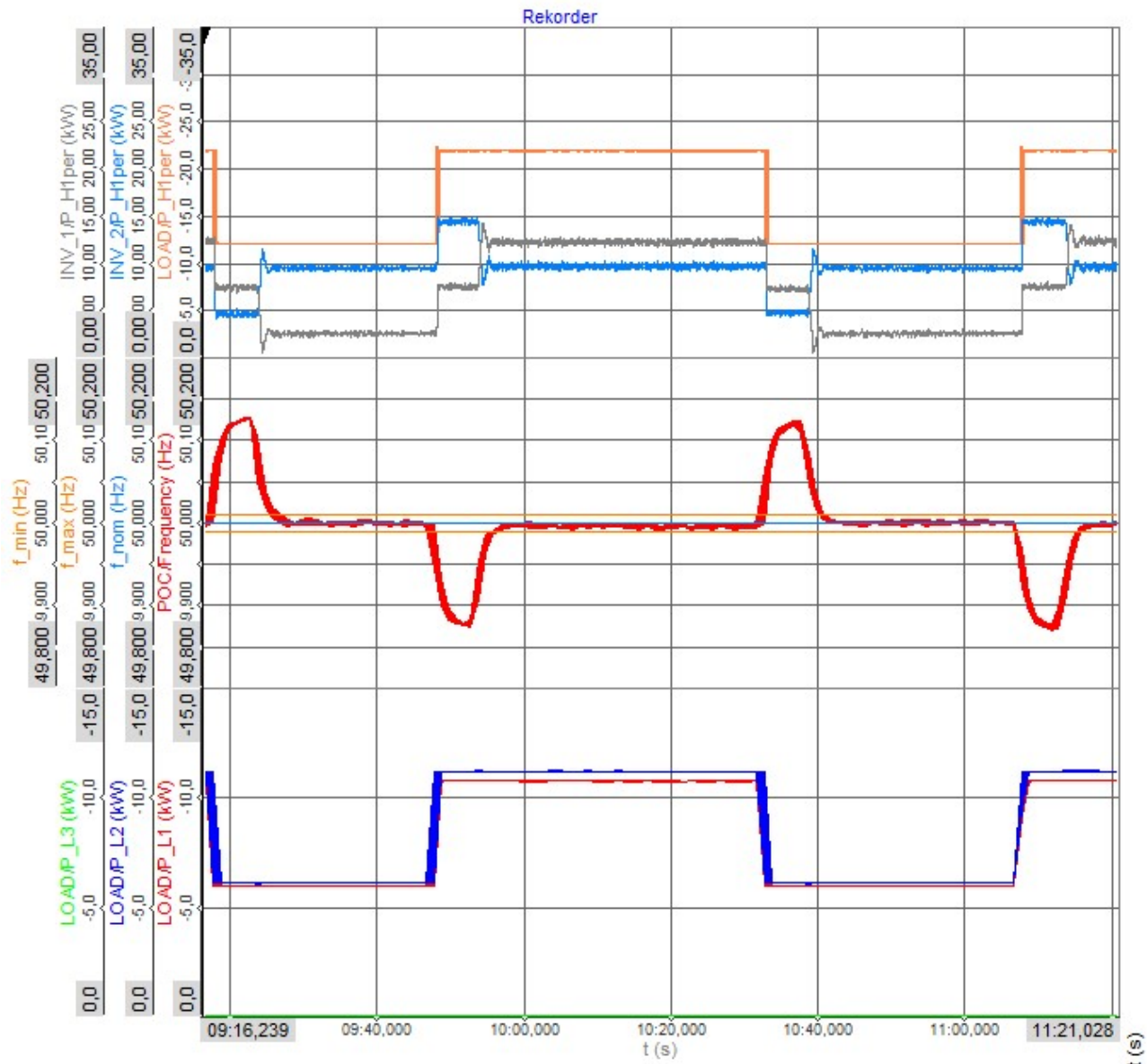


Figure 13: Steady State Islanding – Largest unsymmetrical Load Step.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter;
POC/Frequency: microgrid frequency; f_{nom} - nominal frequency; f_{min}/max : 10 mHz tolerance band;
(P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.1.3 SS-ISL.LS3 Largest Load Step – (Generation < Demand)

The test could not be done at the TECNALIA microgrid laboratory because it was not possible to limit the output power of the inverters so that the available load power in the laboratory was bigger than the maximum generation.

4.2.1.4 SS-ISL.LS4 Largest reactive load (inductive/capacitive)

Table 38: Experiment specification - Largest reactive load (inductive/capacitive)

Title	Largest reactive load (inductive/capacitive)
Ref. Test Specification	SS-ISL LS4
Initial Condition	Same as for experiment specification SS-ISL.LS1
Initiating Event	Steps of reactive power (inductive / capacitive)
Expected insights	Same as for experiment specification SS-ISL.LS1
Metrics	Same as for experiment specification SS-ISL.LS1
Pass / Fail criteria	Same as for experiment specification SS-ISL.LS1

Figure 14 shows several reactive load steps (capacitive). Due to limitations of the grid simulator it was not possible to change the reactive load without changes of active power within this setup. It can be seen that both inverters change its reactive power output (INV_1/Q_H1per, INV_2/Q_H1per) after changes of the reactive load power (LOAD/Q_H1per).

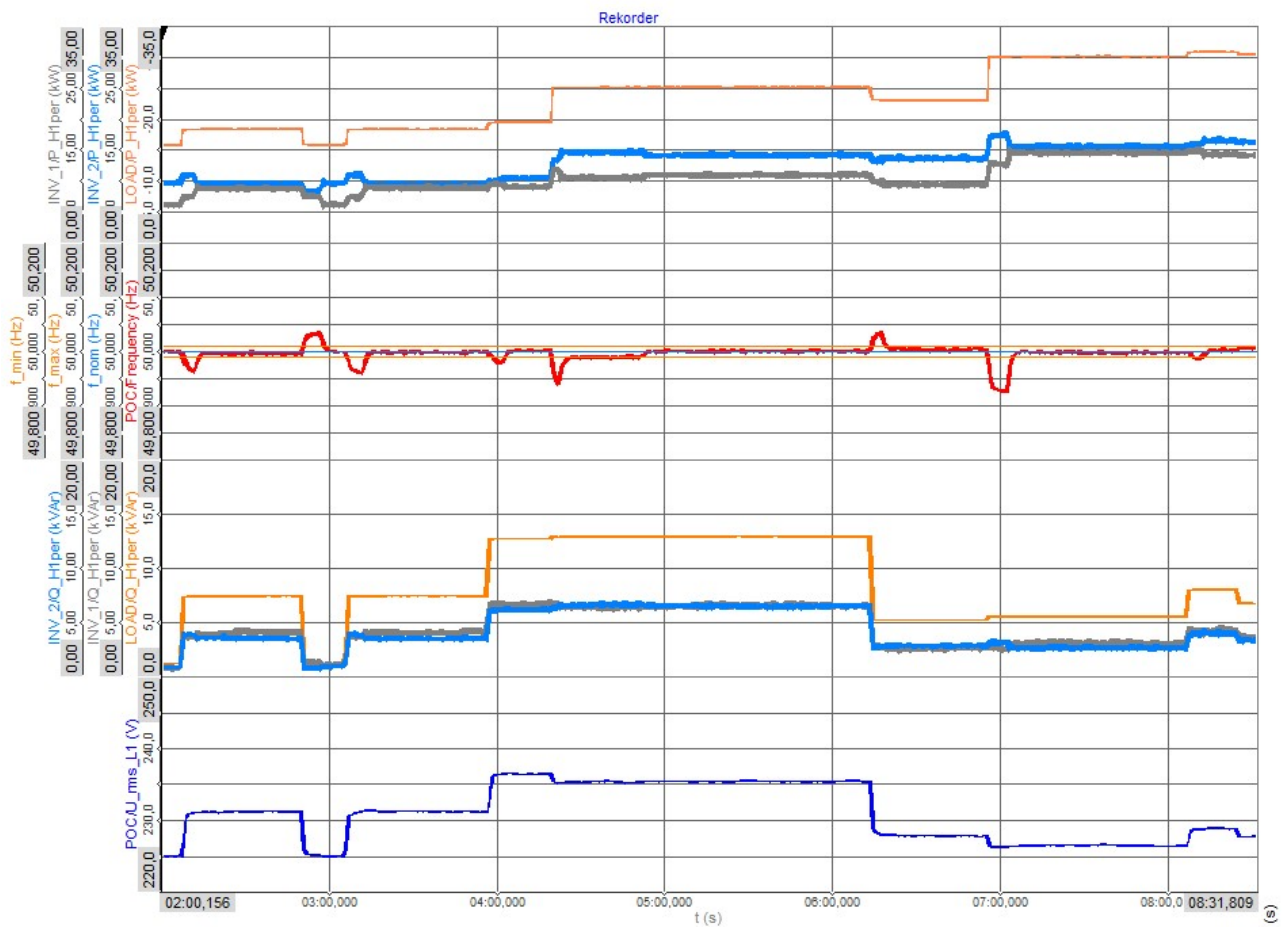


Figure 14: Steady State Islanding – Largest reactive load

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; LOAD/Q_H1per: load reactive power; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/Frequency: microgrid frequency; f_{nom} - nominal frequency; f_{min}/max : 10 mHz tolerance band; POC/U_RMS_L1: RMS voltage, line 1 at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.1.5 SS-ISL.DERT1: DER Trip (Generation > Demand)

Table 39: Experiment specification - DER Trip (Generation > Demand)

DER-trip1	DER-trip1
Ref. Test Specification	<i>SS-ISL DERTRip1</i>
Initial Condition	Same as for experiment specification SS-ISL.LS1
Initiating Event	<i>Manual disconnection of inverter 1</i>
Expected insights	Same as for experiment specification SS-ISL.LS1
Metrics	Same as for experiment specification SS-ISL.LS1
Pass / Fail criteria	Same as for experiment specification SS-ISL.LS1

Figure 15 shows the DER trip in islanded mode. Inverter 1 disconnects at the position of the vertical line in the figure. Inverter 2 increases immediately the power to supply the load of approx. 27 kW. After a few seconds a short negative power flow of 20 kW occurs at inverter 1. Hence, inverter 2 has to supply the power for the load and inverter 2, in total 50 kW which is above its rated power and could lead to a failure. The voltage is increased briefly to around 250 V (detail in Figure 16). The reason for this behavior is unknown and in principle undesired. The test is repeated and shown in Figure 17. A lower negative power flow occurs and the reactive power and voltage peak in the positive direction is smaller but a higher voltage sag to around 180 V occurred.

The bidding bid for the disconnected inverter 1 had to be removed manually in the parametrization of the secondary control after the DER trip. Otherwise the frequency was not recovered to 50 Hz. Therefore, the settling time is not determined for this test. This could be defined as a fail of the microgrid control system. As the microgrid is still in operation a possible distinction between minor and major failure can be introduced for future standardization efforts.

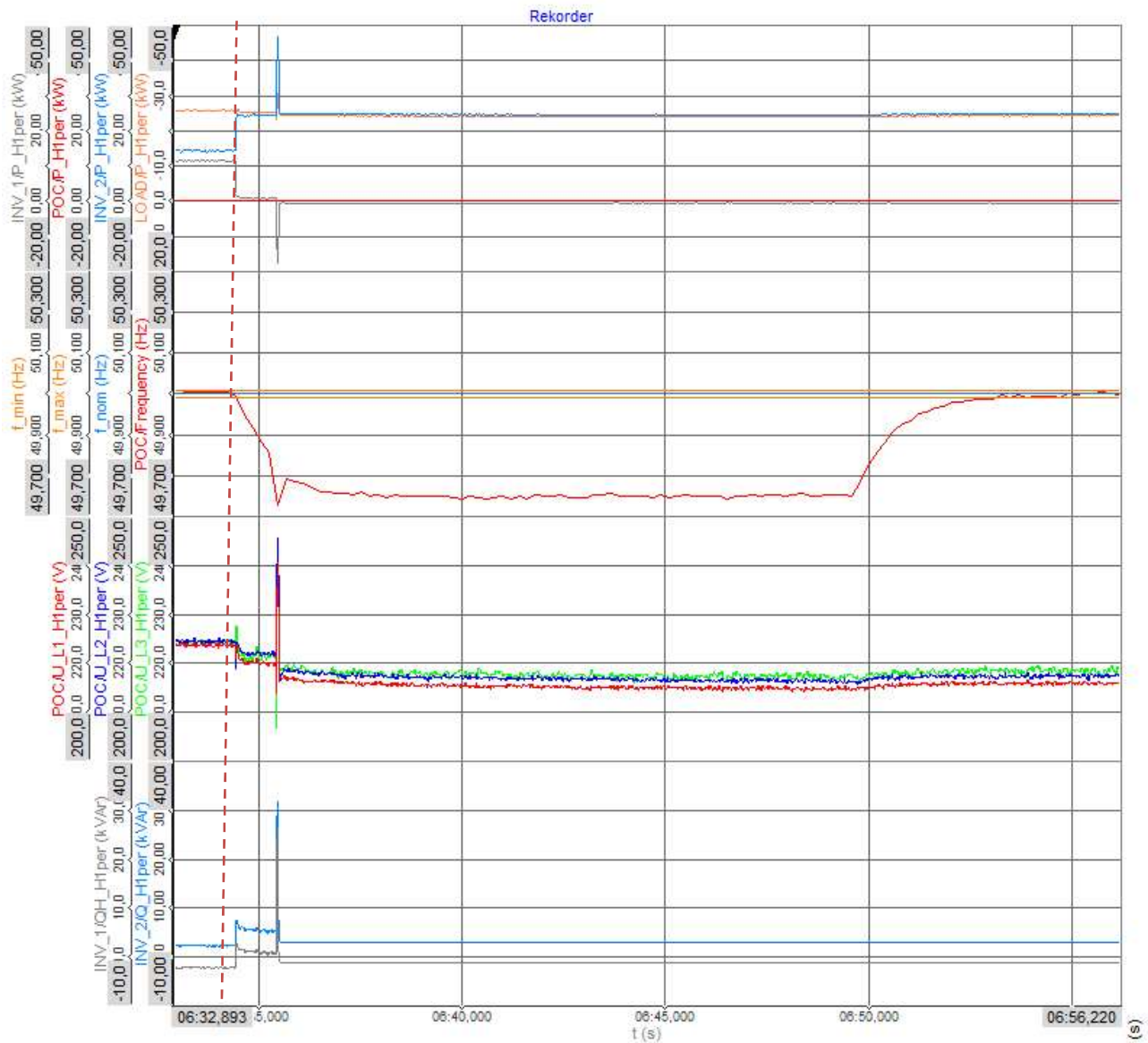


Figure 15: Steady State Islanding, DER Trip - Test 1

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/P_H1per: Active power at the POC; POC/Frequency: microgrid frequency; f_{nom} - nominal frequency; f_{min}/max : 10 mHz tolerance band; POC/U_L1_H1per, POC/U_L2_H1per, POC/U_L3_H1per: voltage, line 1,2,3 at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

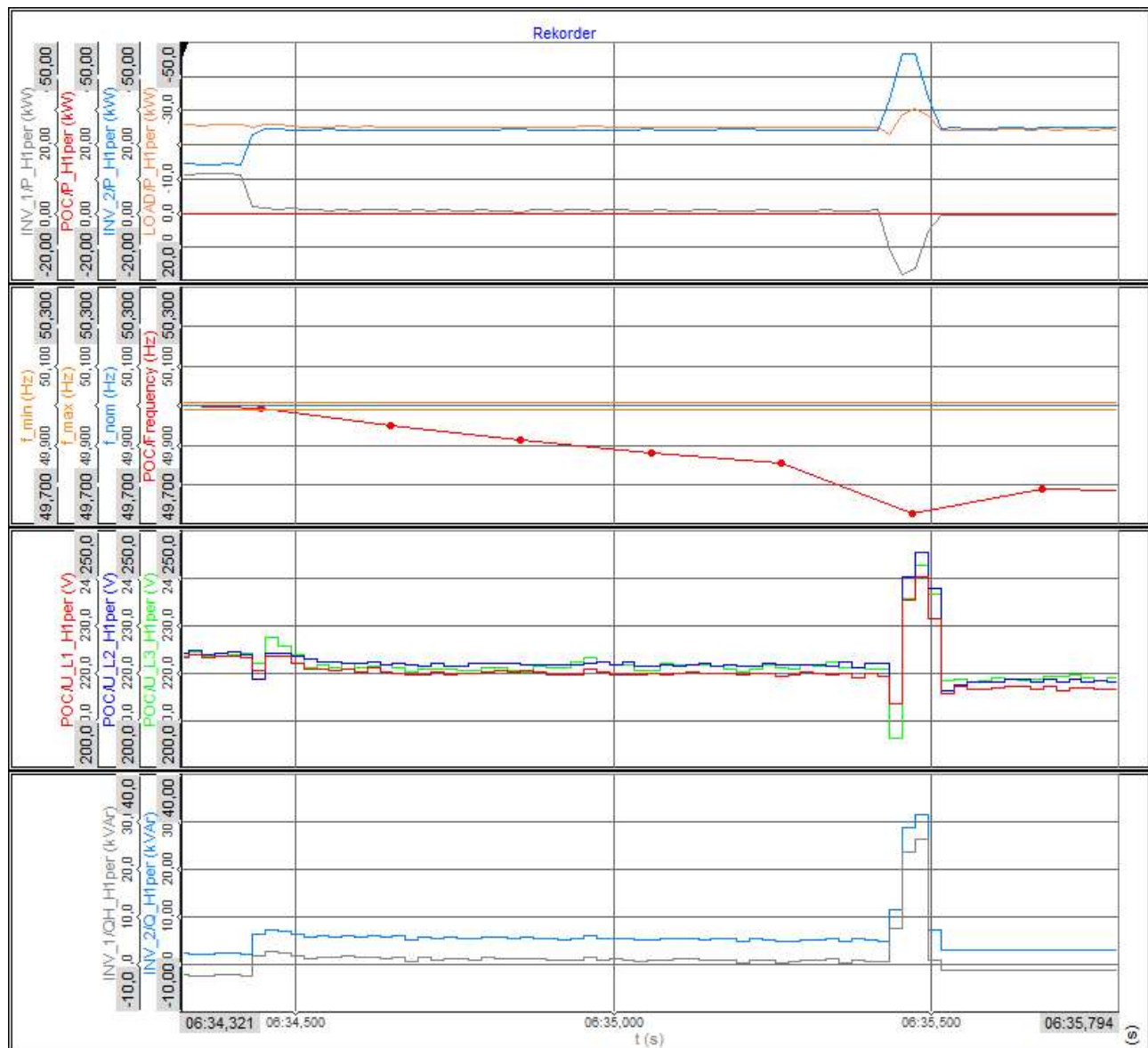


Figure 16: SS-ISL, DER Trip –Test 1: Detailed view after disconnection – negative power cons. of inv. 1

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/P_H1per: Active power at the POC; POC/Frequency: microgrid frequency; f_{nom} - nominal frequency; f_{min}/max : 10 mHz tolerance band; POC/U_L1_H1per, POC/U_L2_H1per, POC/U_L3_H1per: voltage, line 1,2,3 at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

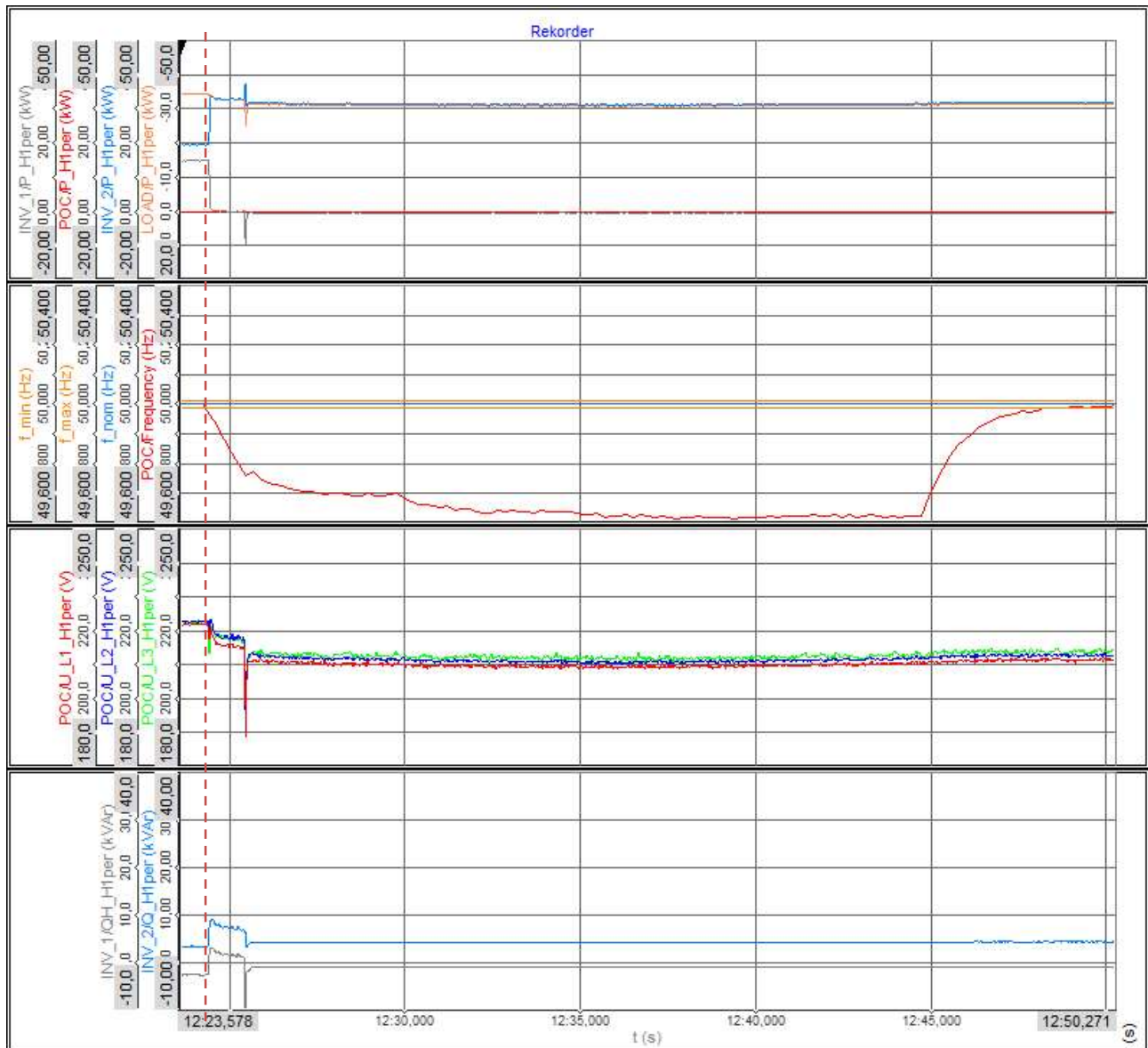


Figure 17: Steady State Islanding, DER Trip - Test 2

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/P_H1per: Active power at the POC; POC/Frequency: microgrid frequency; f_{nom} - nominal frequency; f_{min}/max : 10 mHz tolerance band; POC/U_L1_H1per, POC/U_L2_H1per, POC/U_L3_H1per: voltage, line 1,2,3 at the POC (P_{per} : one period RMS; P_{H1per} : fundamental component of one period RMS)

4.2.1.6 SS-ISL.DERT2: DER Trip – (Generation < Demand)

The test could not be done at the TECNALIA microgrid laboratory because the remaining power capability of the second inverter after the trip of inverter 1 is still higher than the maximum available load power.

4.2.1.7 SS-ISL.DER_Steps: Varying DER generation

Table 40: Experiment specification SS-ISL.LS1

Title	DER steps, varying DER generation
Ref. Test Specification	<i>SS-ISL.DER_Steps</i>
Initial Condition	<ul style="list-style-type: none"> - Power Breaker at POC: Open - Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) - Inverter 1 operates in 'current control' mode - Secondary Control: activated
Initiating Event	<i>DER step, changing power of inverter 1</i>
Expected insights	<ul style="list-style-type: none"> - <i>Is the microgrid able to keep the balance between demand and generation</i> - <i>Does frequency and voltage stay in the desired bandwidth.</i> - <i>Does the dispatch objective is maintained according to the bidding strategy "Reduction of the electricity price depending on the marginal generation costs"</i>
Metrics	Same as for experiment specification SS-ISL.LS1
Pass / Fail criteria	Same as for experiment specification SS-ISL.LS1

Figure 18 shows increasing and decreasing power steps of inverter 1. Inverter 2 adapts its output power immediately after the steps and the secondary control recovers the frequency to 50 Hz. The power of the load increased with the voltage, because a pure resistive load is used. Delay and settling time are given in Table 41. The second test is shown in Figure 19, in which the output power of inverter 1 is increased and decreased iteratively. The power is changed after the frequency recovery of the prior step.

Table 41: SS-ISL.DER_Steps: DER output power steps

	Unit	Step 1	Step 2	Step 3	Step 4	Step 5
P_{load} (before step)	kW	18.9	19	19.1	19.4	19.5
P_{DER,start}	kW	1.6	4.5	9.4	16.3	18.4
P_{DER,end}	kW	4.6	9.5	16.3	18.4	4.6
ΔP_{DER}	kW	3.0	5.0	6.9	2.1	-13.8
P_{inv 1,settled}	kW	1.6	9.6	16.5	18.5	4.6
P_{inv 2,settled}	kW	17.4	5.6	3.1	1.2	14.4
f_{deviation}	Hz	50.08	50.11	50.17	50.05	49.70
f_{delta,max,Step}	Hz	0.08	0.11	0.17	0.05	-0.33
U_{settled 10s_avg}	V	221.8	222.4	223.8	225.4	215.2
U_{max,Step 10s_avg}	V	224.8	225.0	227.8	227.7	223.8
U_{min,Step 10s_avg}	V	218.6	219.52	220.3	221.3	221.08
t_d	s	6.9	3.9	6.4	/	5.5
t_s	s	8.0	9.2	9.0	8.0	10.8

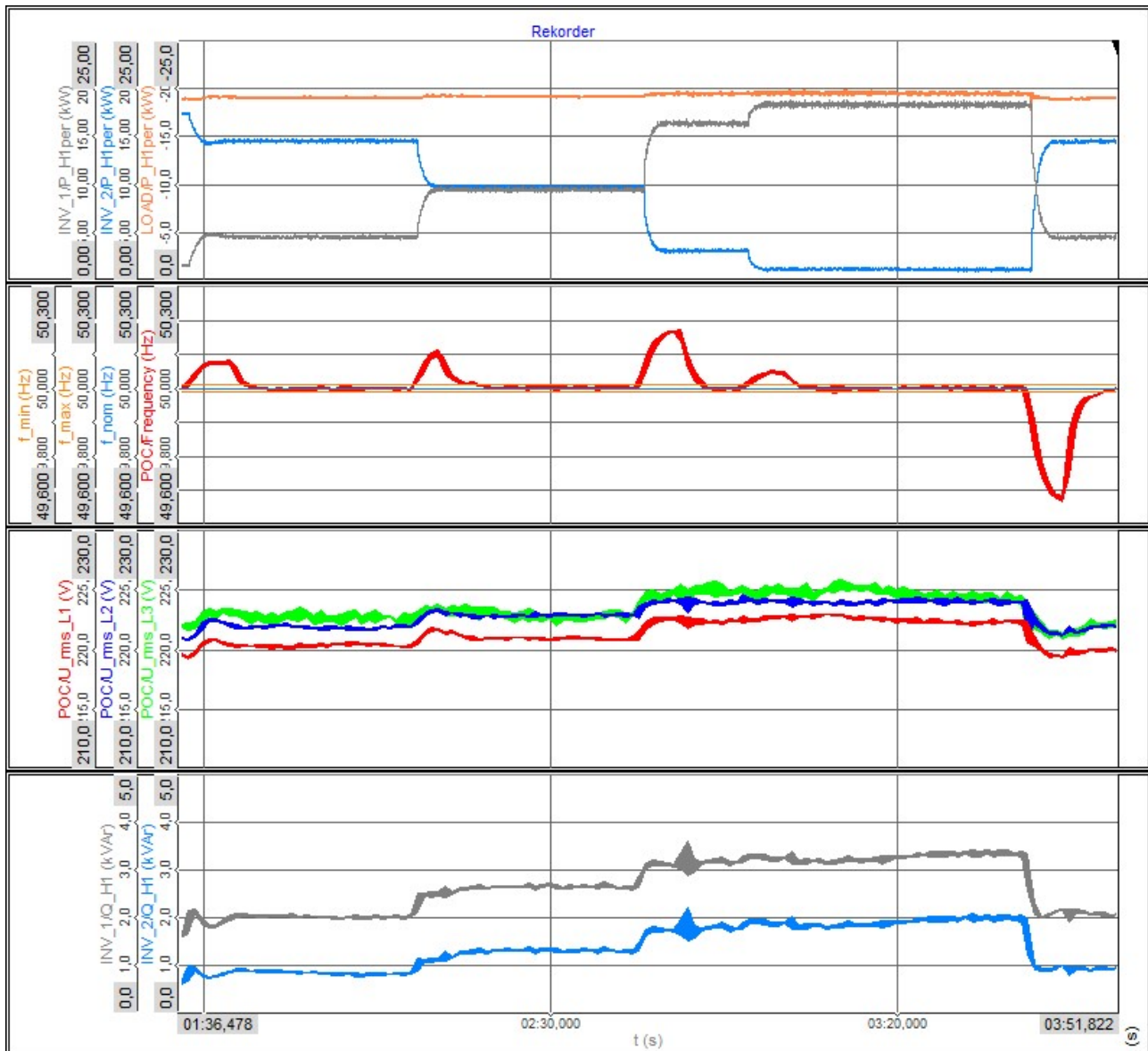


Figure 18: SS-ISL.DER_Steps: DER output power steps

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/Frequency: microgrid frequency; f_nom - nominal frequency; f_min/max: 10 mHz tolerance band; POC/U_rms_L1, POC/U_rms_L2, POC/U_rms_L3: voltage line 1,2,3 at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

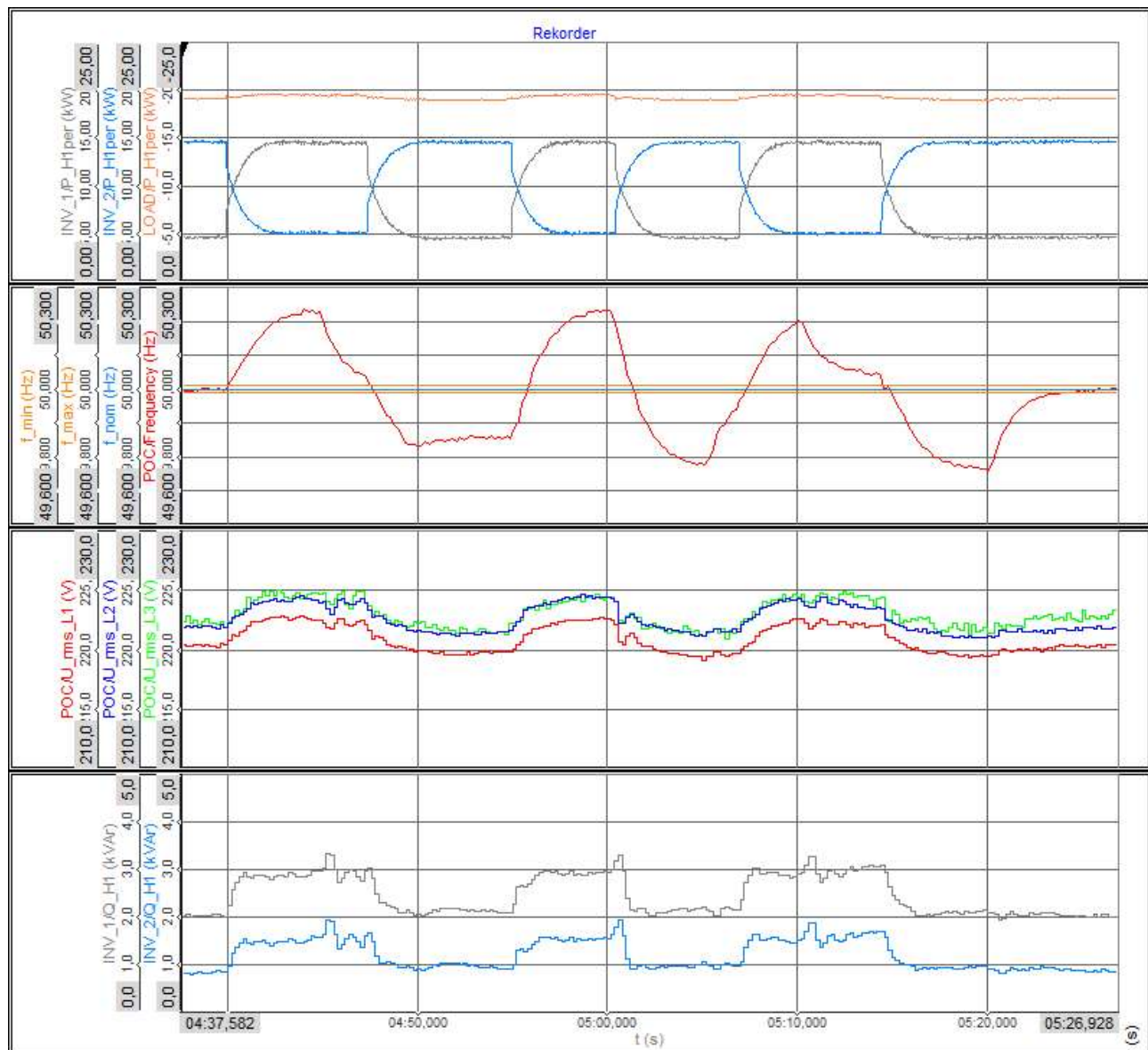


Figure 19: Repeated DER output power steps

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/Frequency: microgrid frequency; f_nom - nominal frequency; f_min/max: 10 mHz tolerance band; POC/U_rms_L1, POC/U_rms_L2, POC/U_rms_L3: voltage, line 1,2,3 at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.2 SS-GCN: Steady State Grid Connected

4.2.2.1 SS-GCN.LS1: Load Step - Zero power flow at POC

Table 42: Experiment specification SS-GCN-LS1 Load step - Zero power flow at POC

Title	Load Step – Zero power flow at POC
Ref. Test Specification	SS-GCN.LS1
Initial Condition	<ul style="list-style-type: none"> - Power Breaker at POC: Closed - Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) - Secondary Control: activated and zero power flow at POC requested
Initiating Event	<ol style="list-style-type: none"> 1. Turn on largest load 5: 16.6 kW 2. Wait until steady state is reached or abort after X seconds if steady state is not reached 3. Turn off largest load <p>Repeat step 1 to 3 three times. Eventually repeat test with another bidding strategy</p>
Expected insights	Is the desired power exchange with the grid maintained within the chosen tolerance band?
Metrics	Settling time t_s as time between the load step and reentry of the power at the POC into the tolerance band. The chosen tolerance band is Zero \pm 3 kW.
Pass / Fail criteria	/

Test 1 - No load shedding

The first load step is shown in Figure 20. The power at the POC (POC/P_H1per) is oscillating strongly around the zero line. A detailed look visualizes that the grid frequency oscillates during the test. Within this microgrid the primary droop-control of the inverters is activated in islanded and grid-connected mode. It leads to the fact that the inverter power also follows the grid frequency in grid-connected mode, which is an undesired behavior. The same applies to the droop control for voltage and reactive power.

After 3:47 minutes the power at the POC enters the tolerance band but it looks as it would probably leave it again if the step would be held longer. The maximum feed-in power during this time reached 6.5 kW, the maximum consumption power 3.9 kW. An insight of this test, not only the chosen tolerance band but also step holding time can cause under certain circumstances different results for the settling time.

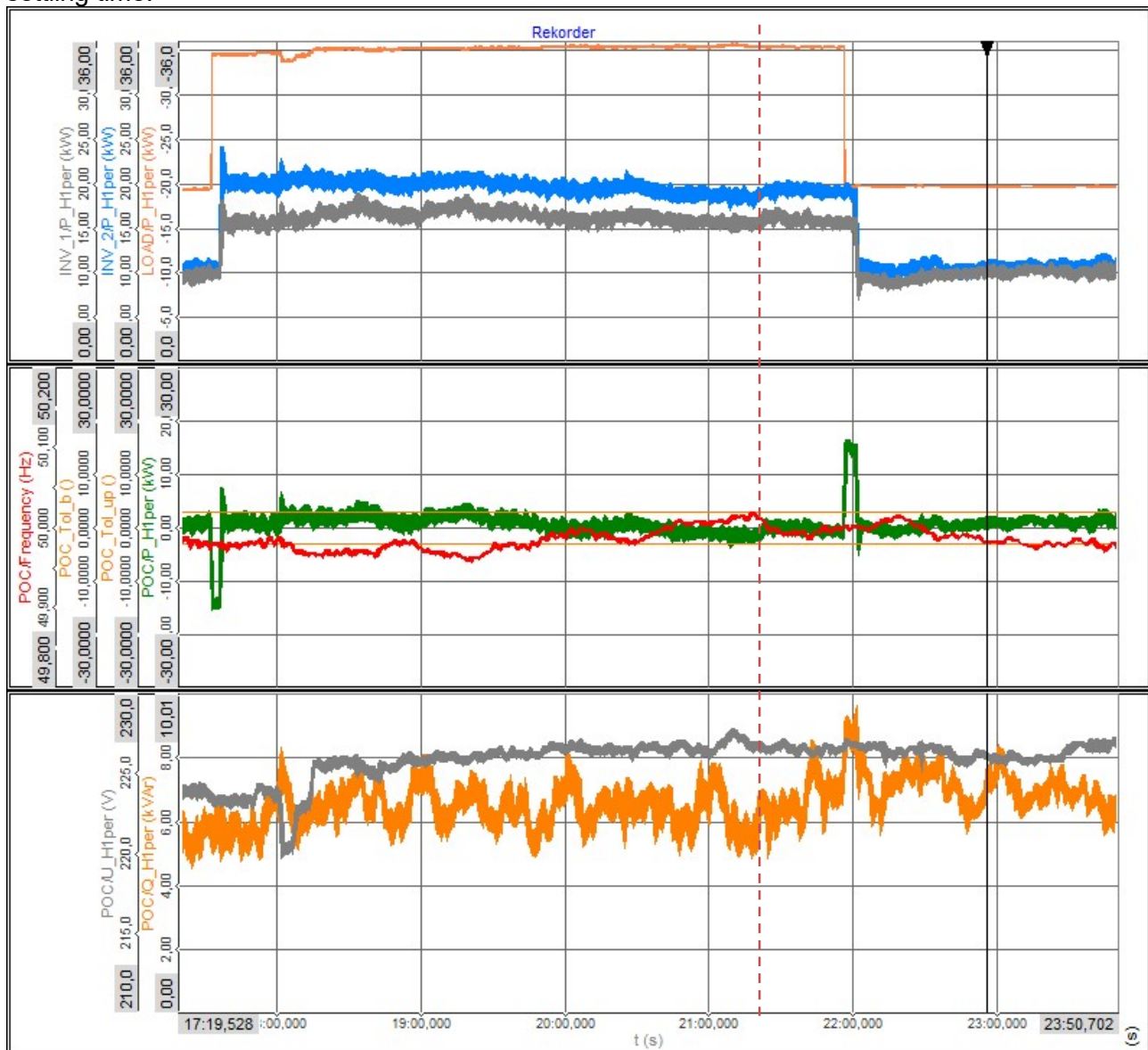


Figure 20: SS-GCN.LS1 Load step - Zero power flow at POC

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; INV_1/Q_H1per, INV_2/Q_H1per: reactive power of the first and second inverter; POC/Frequency: microgrid frequency; POC_tol_b, POC_tol_up tolerance band; POC/U_H1per: Voltage at the POC; POC/P_H1per: Active power at the POC, POC/Q_H1per: Reactive power at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

Test 2 - Load shedding

This test validates if load shedding is initiated from the MGCS and the desired power exchange at the POC is maintained. The test is shown in Figure 21. The load shedding is done 6.3 s after the load step and the power at the POC (POC/P_H1per) enters and stays within the tolerance band 7 s after the step.

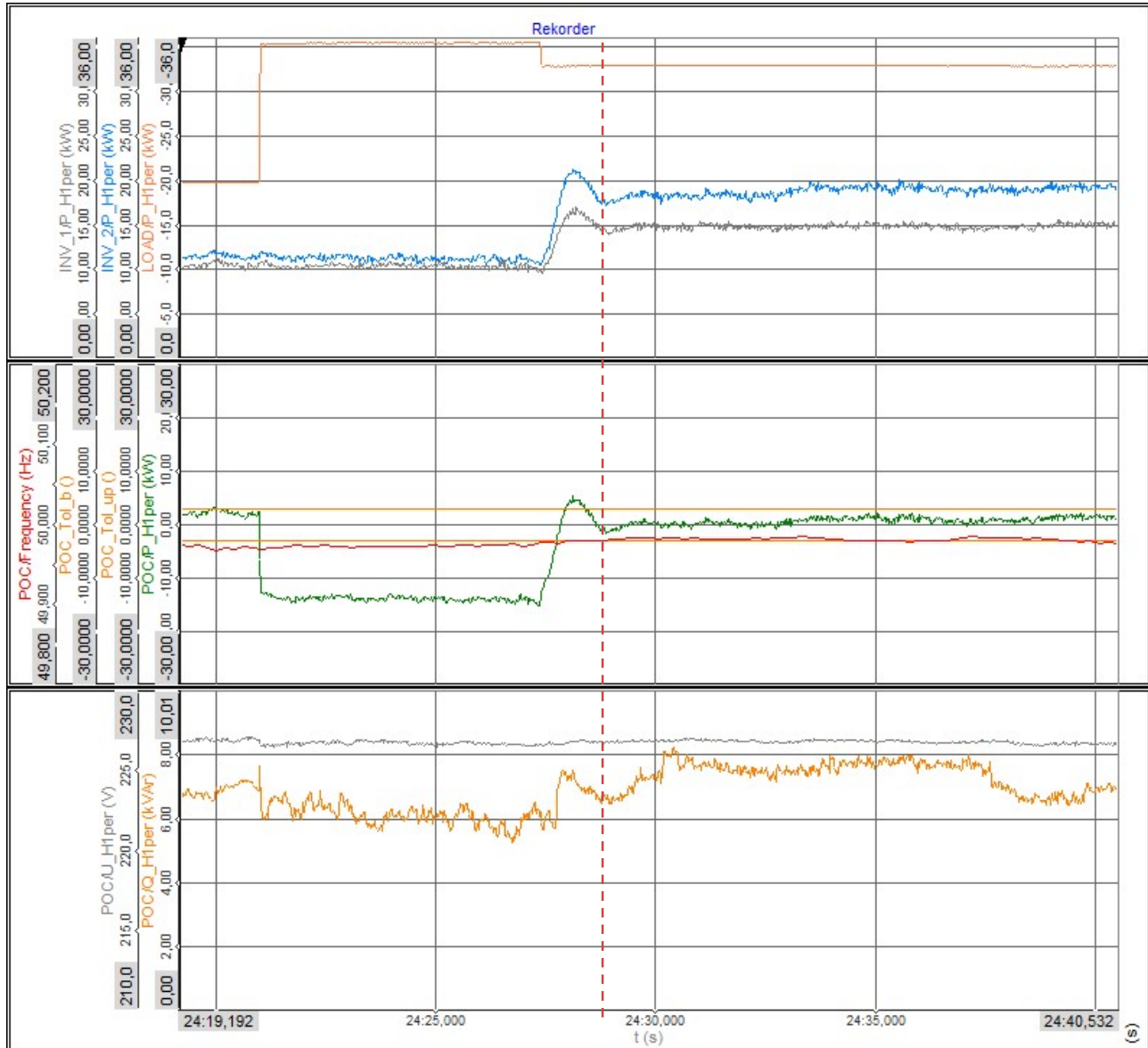


Figure 21: SS-GCN.LS1 Load step - Zero power flow at POC, including load shedding.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; POC_tol_b, POC_tol_up tolerance band; POC/U_H1per: Voltage at the POC; POC/P_H1per: Active power at the POC; POC/Q_H1per: Reactive power at the POC (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.2.2 SS-GCN.LS2: Load Step - Import power flow at POC

Table 43: Experiment specification SS.GCN-LS2 Load step - Import power flow at POC

Title	<i>Load Step – Import power flow at POC</i>
Ref. Test Specification	<i>SS-GCN.LS2</i>
Initial Condition	<ul style="list-style-type: none"> - <i>Power Breaker at POC: Closed</i> - <i>Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage)</i> - <i>Secondary Control: activated and 10 kW import power at POC requested</i>
Initiating Event	<i>Same as experiment specification SS-GCN.LS1</i>
Expected insights	<i>Same as experiment specification SS-GCN.LS1</i>
Metrics	<i>Same as experiment specification SS-GCN.LS1</i>
Pass / Fail criteria	<i>Same as experiment specification SS-GCN.LS1</i>

The test is done without load shedding and shown in Figure 22. After the initiating event (load step) the power is kept within the chosen tolerance band ± 3 kW. Briefly before the next load step the power leaves the tolerance band for a short time but returns to it again.

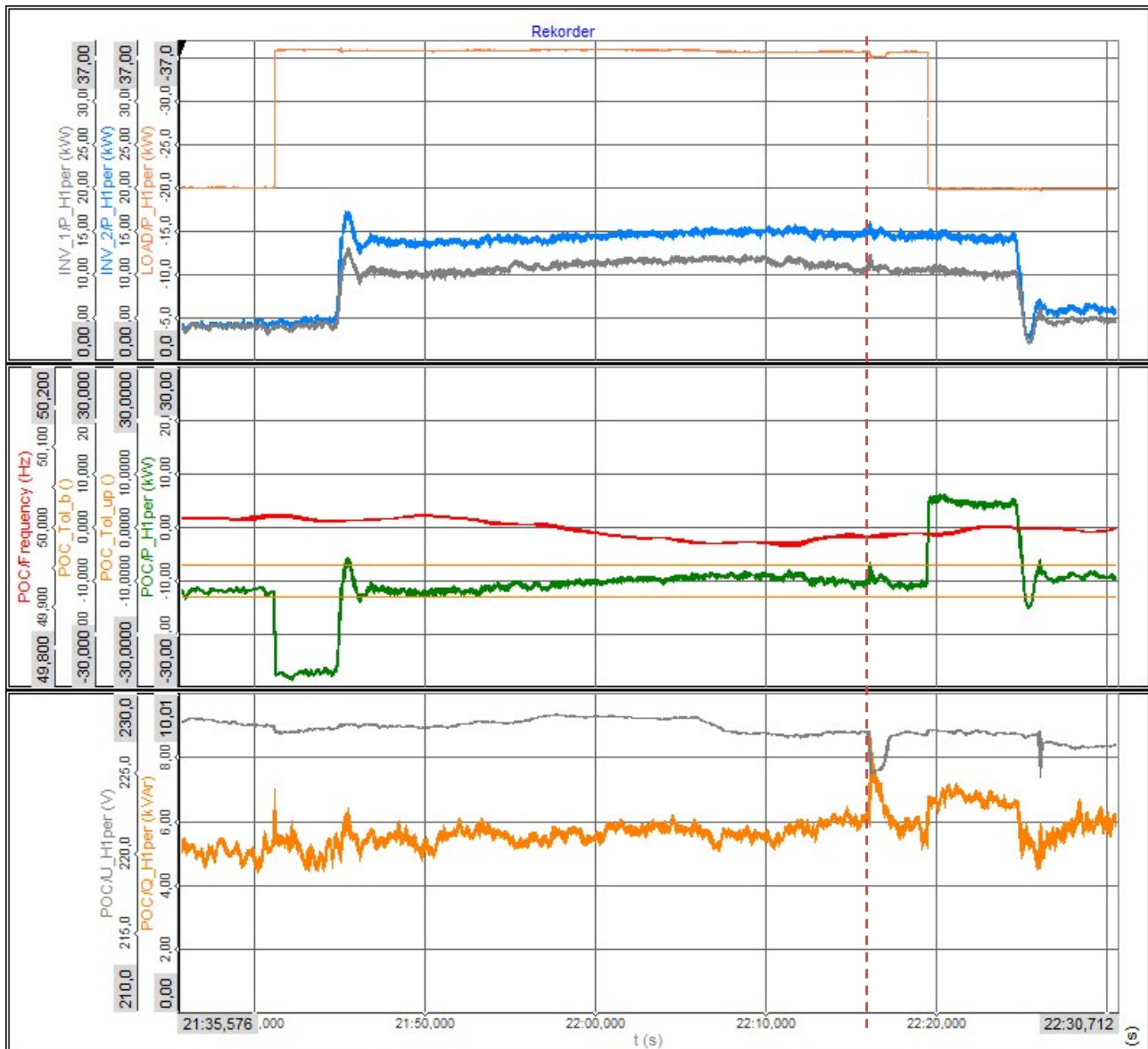


Figure 22: SS-GCN.LS2 Load step - Import power flow at POC without load shedding.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; POC_tol_b, POC_tol_up tolerance band; POC/U_H1per: Voltage at the POC; POC/P_H1per: Active power at the POI; POC/Q_H1per: Reactive power at the POI (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.2.3 SS-GCN.LS3: Load Step - Export power flow at POI

Table 44: Experiment specification SS-GCN.LS3 Load step - Export power flow at POC

Title	Load Step – Export power flow at POI
Ref. Test Specification	SS-GCN.LS3
Initial Condition	<ul style="list-style-type: none"> - Power Breaker at POI: Closed - Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) - Secondary Control: activated and 10 kW export power at POI requested
Initiating Event	Same as experiment specification SS-GCN.LS1
Expected insights	Same as experiment specification SS-GCN.LS1
Metrics	Same as experiment specification SS-GCN.LS1
Pass / Fail criteria	Same as experiment specification SS-GCN.LS1

The test is performed without load shedding (Figure 23) and with load shedding (Figure 24). The requested power is maintained within the specified tolerance band of 10 kW \pm 3 kW. The settling time for the test without load shedding is given in Table 45.

At the second test, load shedding is done properly by the MGCS and the power at the POI enters and stays within the tolerance band.

Table 45: Settling time SS-GCN.LS3 Load step - Export power flow at the POI Test 1

	Unit	Load step 1	Load step 2
ΔP	kW	15.8	-15.8
t_d	s	4.3	5.4
t_s	s	5.1	6.4

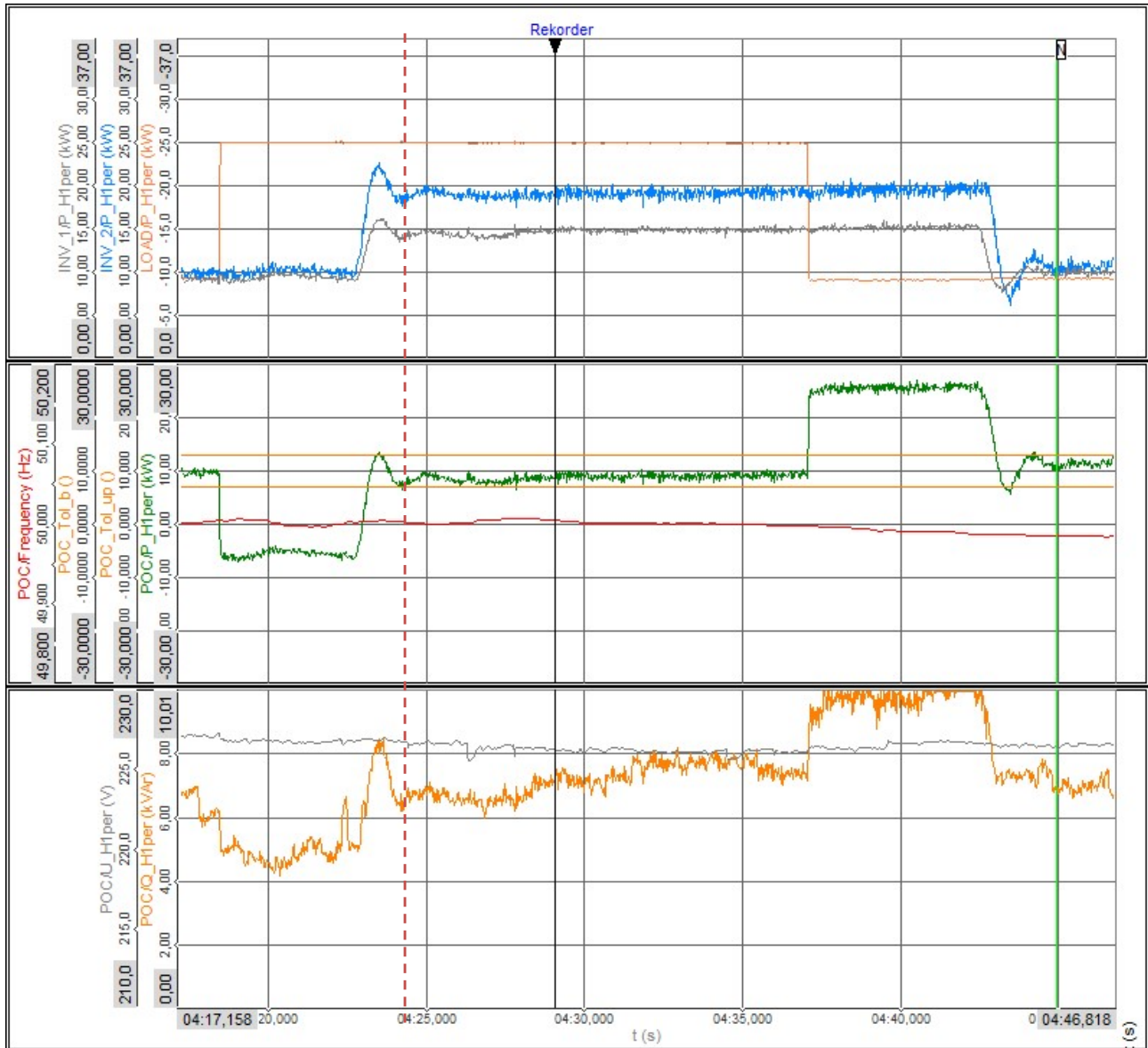


Figure 23: SS-GCN.LS1 Load step - Export power flow at POC without load shedding

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; POC_tol_b, POC_tol_up tolerance band; POC/U_H1per: Voltage at the POI; POC/P_H1per: Active power at the POI; POC/Q_H1per: Reactive power at the POI (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

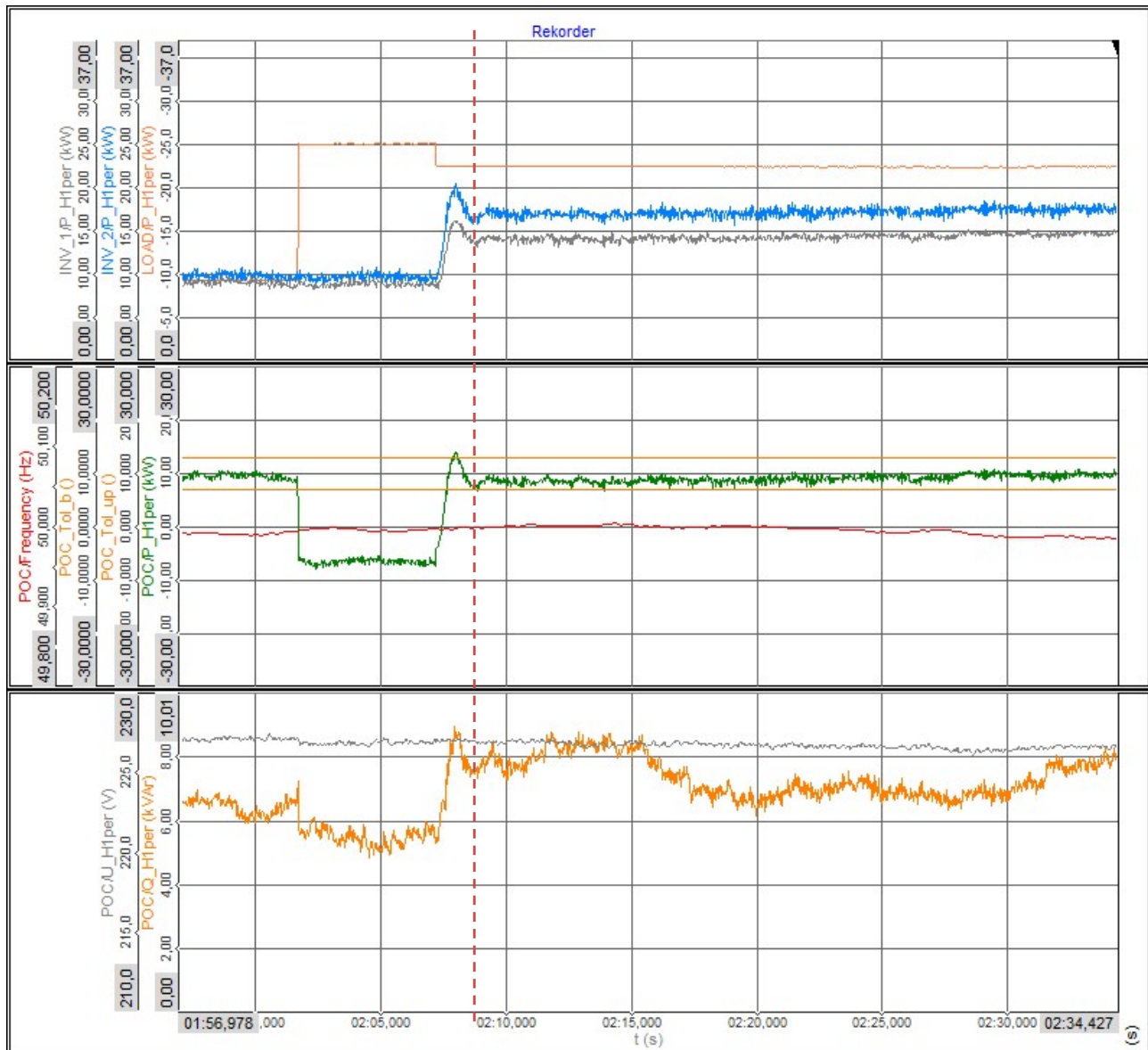


Figure 24: SS-GCN.LS1 Load step - Export power flow at POC including load shedding.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; POC_tol_b, POC_tol_up tolerance band; POC/U_H1per: Voltage at the POI; POC/P_H1per: Active power at the POI; POC/Q_H1per: Reactive power at the POI (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.2.4 SS-GCN.DER Trip

Table 46: Experiment specification – SS-GCN.DER Trip

DER-trip1	DER-trip1
Ref. Test Specification	SS-GCN.DER Trip
Initial Condition	<ul style="list-style-type: none"> - POI breaker is closed - A specific power at the POI is set - A base load is on e.g. same as SS-ISL.LS1
Initiating Event	Manual disconnection of inverter 1
Expected insights	Is the desired exchange power at the POI maintained
Metrics	Same as for experiment specification SS-ISL.LS1
Pass / Fail criteria	Same as for experiment specification SS-ISL.LS1

Figure 25 shows the DER trip experiment. Zero export power is set for exchange power at the POI with the utility grid. After the DER trip of inverter 1 it consumes briefly 40 kW and inverter 2 has a constant power output. Furthermore, the secondary control is not able to maintain zero power exchange within the tolerance band. Like in the test for islanded mode, the secondary control did not see the disconnection of inverter 1. The information that inverter 1 disconnected had to be sent manually to the secondary control using a reparameterization (c.f. the green cursor in Figure 25). Afterwards the power at the POI entered again the tolerance band.

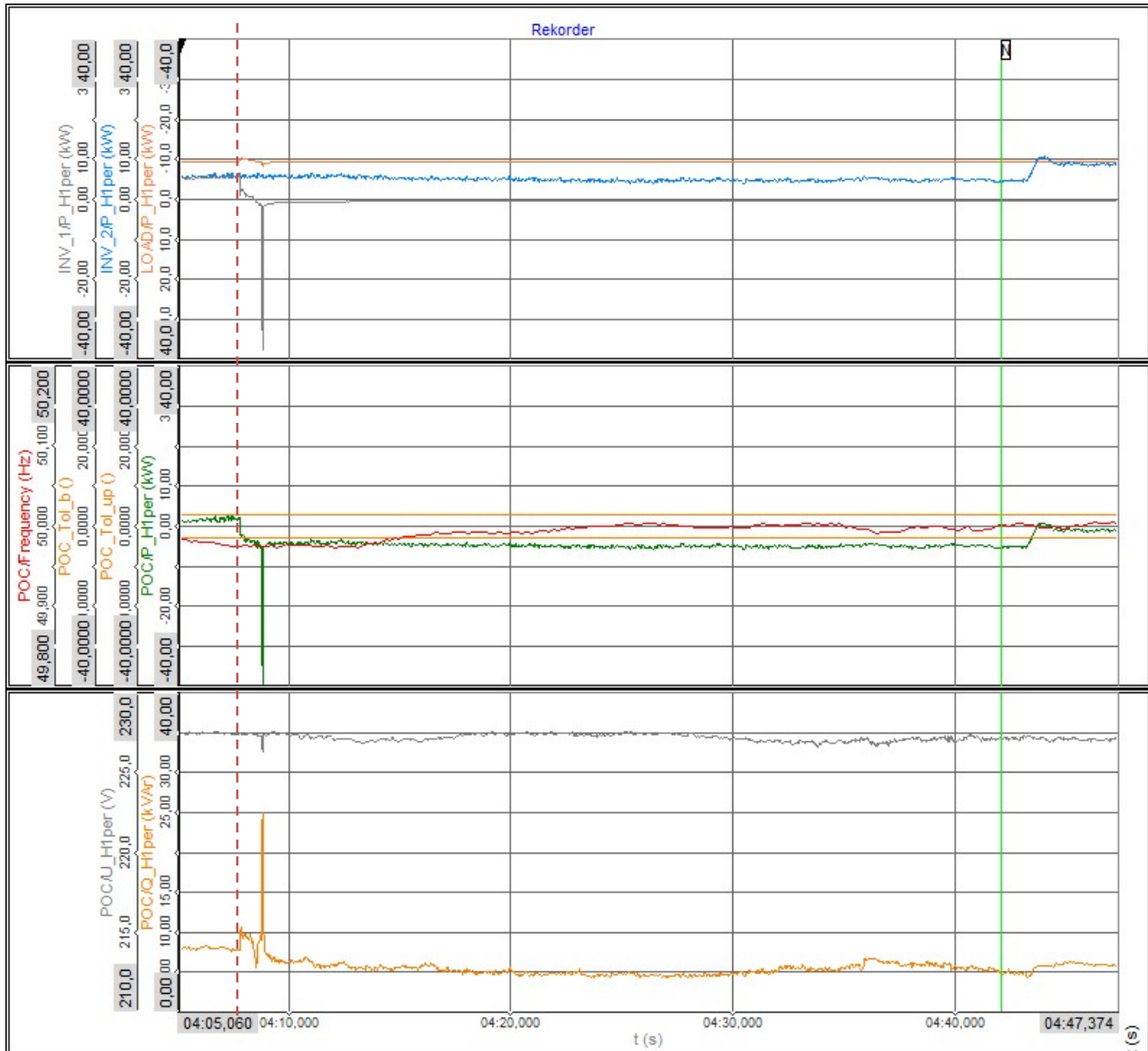


Figure 25: SS-GCN-DERTrip Zero Export power at POC including load shedding.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; POC_tol_b, POC_tol_up tolerance band; POC/U_H1per: Voltage at the POC; POC/P_H1per: Active power at the POI; POC/Q_H1per: Reactive power at the POI (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

4.2.3 PI: Planned Islanding

For the planned islanding test case following scenarios are specified.

1. PI.PE0: Zero grid exchange at POI before islanding
2. PI.PE1: Feed-in at POI before islanding
3. PI.PE1: Power import before islanding
4. PI.S1: $P_{Load} > P_{DER,max}$

Within this work the experiment for **PI.PE0: Zero grid exchange at POI before islanding** is anticipated. Due to a steady state error of the power exchange at the POI it was not possible to set zero power exchange at the POI with the utility grid. Thus scenario 2 with around 3 kW feed in power is tested. As the POI breaker can switch under load it is assumed that test 2-3 are similar to test 1. Test 4 can't be done in the microgrid configuration of TECNALIA due to limitations of the maximum load.

4.2.3.1 PI.PE1: Feed-in at POI before islanding

Table 47: Experiment specification PI.PE1: Feed-in at POI before islanding

Title	Load Step – Feed-in at POI before islanding
Ref. Test Specification	PI.PE1
Initial Condition	<ul style="list-style-type: none"> - Power Breaker at POI: Closed - Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) - Secondary Control: activated - Feed-In Power at the POI measured
Initiating Event	Send islanding signal
Expected insights	<ul style="list-style-type: none"> - Does the POI breaker open? - Is a seamless transition to island mode possible? - Is the frequency and voltage during the transition within the specified limits.
Metrics	Settling time t_s as time between the islanding command and reentry of frequency into tolerance band. The chosen tolerance band is 50 Hz \pm 0.01 Hz.
Pass / Fail criteria	<p>Pass:</p> <ul style="list-style-type: none"> - Seamless transition to islanding mode - Frequency enters and stays within tolerance band - Voltage and frequency within its specification limits <p>Major Failure</p> <ul style="list-style-type: none"> - No islanding possible - Frequency and voltage limits exceeded during transition

The test is shown in Figure 26. The bottom subfigure shows the connection signal. It indicates grid connected (value 1) or islanded (value 0) mode. A load of 20 kW is switched on and supplied by inverter 1 and inverter 2. A small power of 3.5 kW is exported to the utility grid due to a steady state error. After the POI breaker is closed the primary control immediately adapts the power of both inverters and the frequency increases. The secondary control updates the set point with a delay time of 7 s and the frequency is recovered after 8.4 s settling time. Figure 27 shows the test with activated load-shedding (t_1). The islanding is done at time point (t_2) without any issues and the frequency recovered after 5.5 s (t_3)

Figure 28 shows the transient behavior of the currents and a smooth transition phase without any issues is visible. The power harmonics in grid connected mode are high but disappear in island mode.

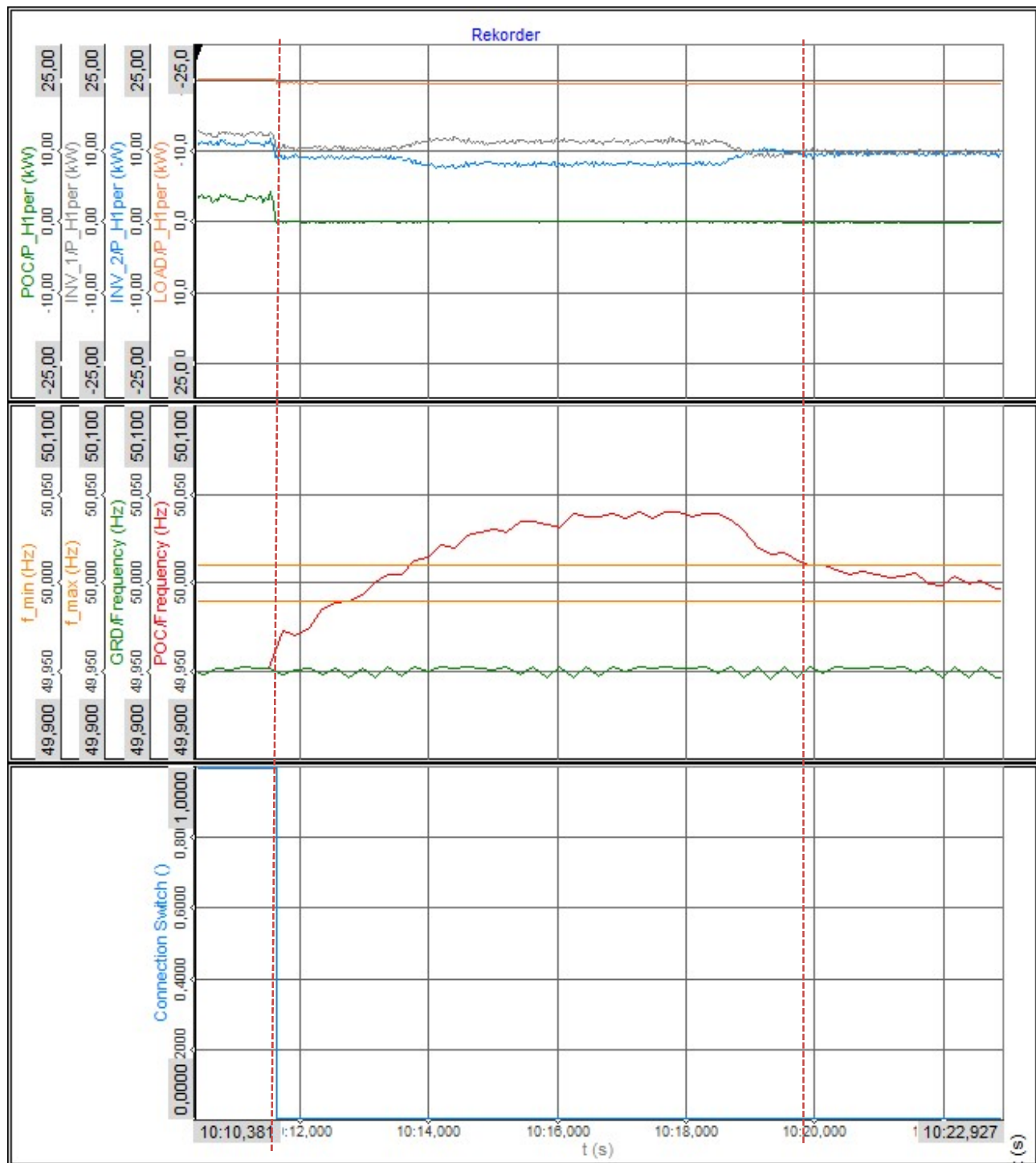


Figure 26: PI.PE0: Low grid exchange power (3.55 kW feed in) at POI before islanding

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; GRD/Frequency: utility grid frequency; f_{min} / f_{max} frequency tolerance band; POC/P_H1per: Active power at the POI; Connection switch: State of POI breaker (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

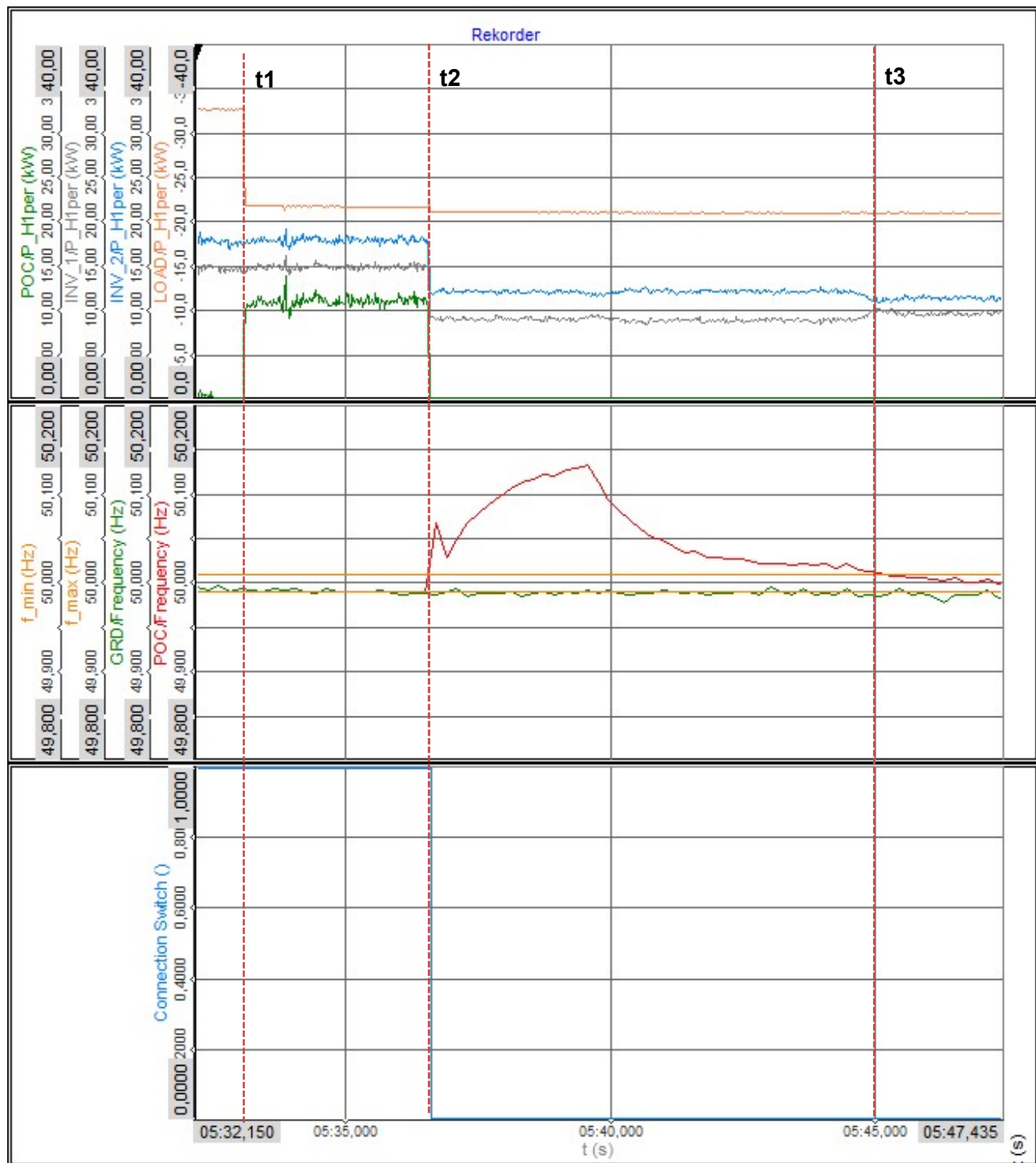


Figure 27: Planned islanding with load-shed before islanding.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; GRD/Frequency: utility grid frequency; f_min / f_max frequency tolerance band; POC/P_H1per: Active power at the POI; Connection switch: State of POI breaker (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

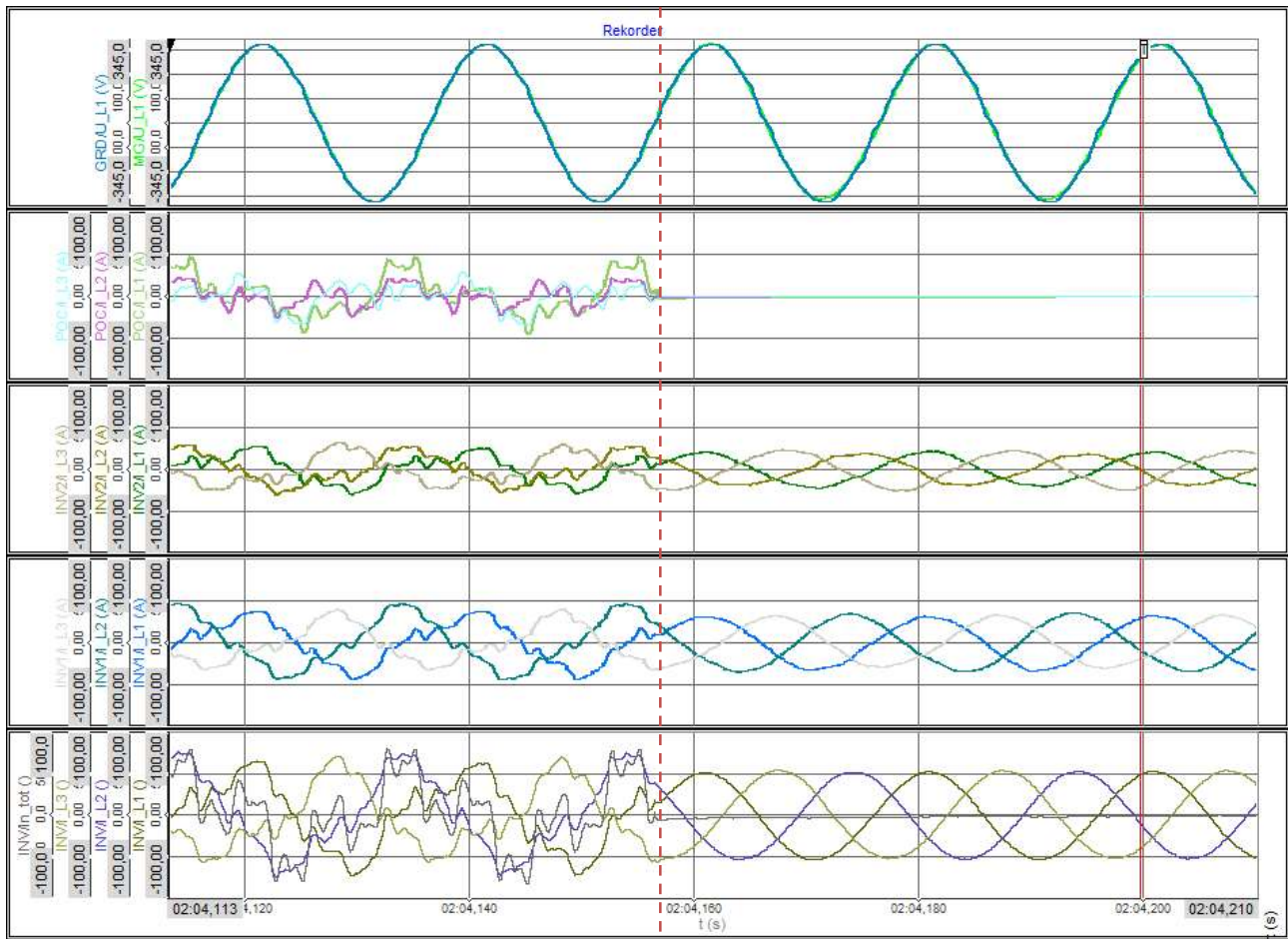


Figure 28: Transient behaviour PI.PE0: Zero grid exchange at POI before islanding.

POC/I....: Phase currents at POI; INV_1,2/I.... Phase currents of the inverters; INV/In_tot: current of inverter 1 and 2 in neutral line; GRD/U_L1: Grid voltage; MG/U_L1: Microgrid voltage)

4.2.4 UPI: Unplanned Islanding

For the unplanned islanding test case following scenarios are specified:

1. UPI.T1: Main Grid / Grid Simulator outage $P_{POC} = 0$.
2. UPI.T2: Main Grid / Grid Simulator outage $P_{POC} > 0$
3. UPI.T3: Grid Voltage/Frequency/Power Quality requires islanding
4. UPI.T4: POI breaker opened manually (if possible $P_{POI} > 0$)

Out of those 4, only Scenario 2 was tested.

4.2.4.1 UPI.T2: Main Grid / Grid Simulator outage $P_{POC} > 0$

Table 48: Experiment specification UPI.T2: Main Grid / Grid Simulator outage $P_{POC} > 0$

Title	Main Grid / Grid Simulator outage $P_{POC} > 0$
Ref. Test Specification	UPI.T2
Initial Condition	<ul style="list-style-type: none"> - Power Breaker at POI: Closed - Grid simulator supplies microgrid - Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) - Secondary Control: activated - Feed-In Power at the POI measured
Initiating Event	Switch grid simulator off or set zero voltage
Expected insights	<ul style="list-style-type: none"> - Is a microgrid in islanded mode formed? - Does the POI breaker open to be conform to anti-islanding requirements in national grid-codes? - Is a seamless transition to island mode after a grid outage is possible? - Is the frequency and voltage within the transition within the specified limits.
Metrics	Settling time t_s as time between the islanding command and reentry of frequency into tolerance band. The chosen tolerance band is 50 Hz \pm 0.01 Hz.
Pass / Fail criteria	<p>Pass:</p> <ul style="list-style-type: none"> - Seamless transition to islanding mode - Frequency enters and stays within tolerance band - Voltage and frequency within its specification limits <p>Major Failure</p> <ul style="list-style-type: none"> - No islanding possible - Frequency and voltage limits exceeded during transition

Figure 29 shows the unintended islanding test scenario. The microgrid is in grid-connected mode and supplied by the grid simulator. At t_1 (left vertical cursor) the AC grid simulator is switched off. The inverters form immediately a microgrid which can be seen on a small frequency and power change. The frequency measured at the grid side (GRD/Frequency) is still the same as the frequency measured at the microgrid side (POC/Frequency) which means the POI breaker did not open. No anti-islanding is done although this is usually required by national grid codes. As there is still voltage on the grid side after the grid outage it can be a danger for workers trying to find the error in the utility grid. The secondary control is not working as there is a frequency deviation and the frequency is below 49.9 Hz. After the POI breaker is opened manually at t_2 (right vertical cursor) the secondary control recovers the frequency to 50 Hz. Now the frequency measurement at the grid side is zero. This test demonstrates that anti-islanding methods and tests for microgrids are an important and crucial topic.

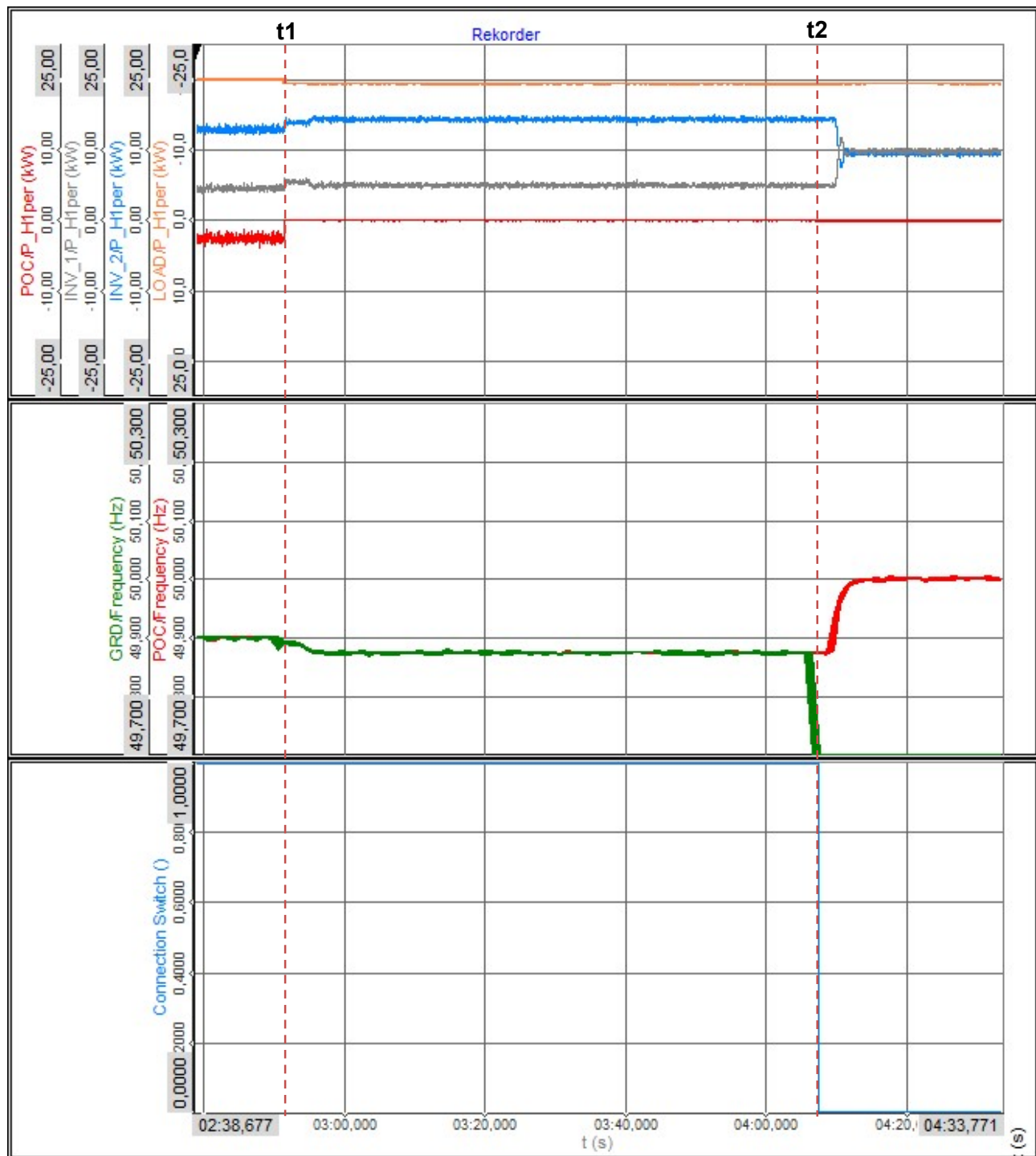


Figure 29: UPI.T2: Main Grid / Grid Simulator outage $P_{POC} > 0$.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; GRD/Frequency: utility grid frequency; f_{min} / f_{max} frequency tolerance band; POC/P_H1per: Active power at the POI; Connection switch: State of POI breaker (P_{per} : one period RMS; P_{H1per} : fundamental component of one period RMS)

4.2.5 RCN: Reconnection – Reconnection signal sent.

Table 49: Experiment specification RCN Reconnection

Title	Reconnection signal sent (Reconnection allowed)
Ref. Test Specification	RC.T1
Initial Condition	<ul style="list-style-type: none"> - Power Breaker at POI: Open - Resistive load: 3 phase symmetrical resistive load: TECNALIA load cascade: Load 1 + Load 2 + Load 3 + Load 4 ~ 21.8 kW (actual power depends on voltage) - Secondary Control: activated - Reconnection is allowed: utility grid is available and frequency and voltage within specifications.
Initiating Event	Send reconnection signal
Expected insights	<ul style="list-style-type: none"> - Does the microgrid reconnects to the grid - Is the frequency and voltage during the transition within the specified limits.
Metrics	
Pass / Fail criteria	<p>Pass:</p> <ul style="list-style-type: none"> - Seamless transition to grid-connected mode <p>Major Failure</p> <ul style="list-style-type: none"> - No reconnection possible - Frequency and voltage limits exceeded during transition

The reconnection is shown in Figure 30. The microgrid operates in islanded mode with a base load of 10 kW. The reconnection signal is sent at time point 't1'. The inverters increase the frequency to accelerate the synchronization process for matching the same phase angle on utility and grid side. At 't2' it matches, and the POI breaker closes. The transition is done at 50.05 Hz. As there are no rotating machines within the microgrid it is not necessary that the frequency of utility and microgrid matches exactly at the time of the reconnection. The synchronization took 7.6 seconds. The power at the POI after the reconnection is close to zero. Figure 31 shows the second test. The reconnection starts from a lower frequency because the secondary control did not work before the reconnection. Figure 32 and Figure 33 show the transient behavior at the reconnection. No critical issues are observed.

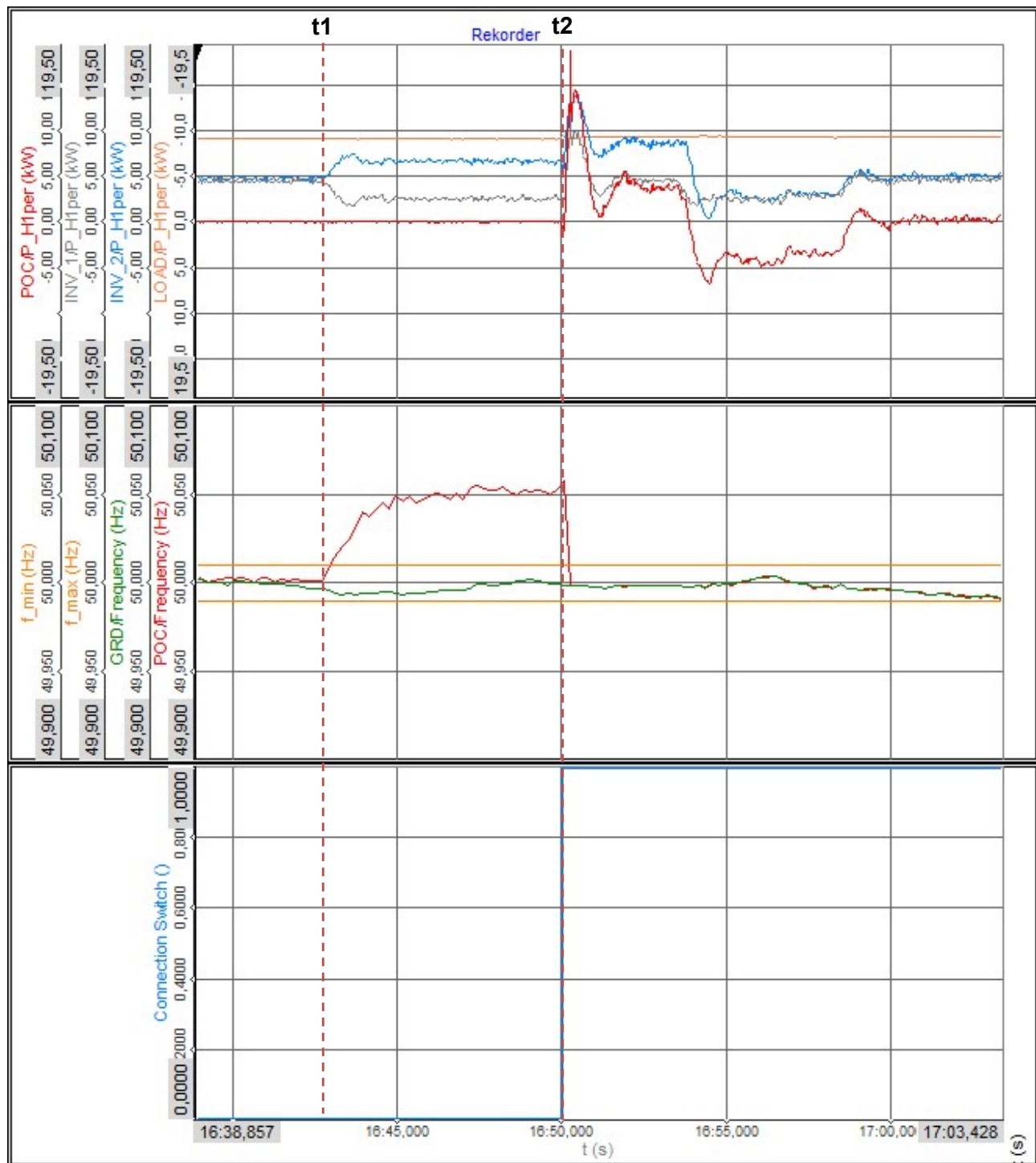


Figure 30: RC.T1 Reconnection Test 1.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; GRD/Frequency: utility grid frequency; f_{min} / f_{max} frequency tolerance band; POC/P_H1per: Active power at the POI; Connection switch: State of POI breaker (P_per: one period RMS; P_H1_per: fundamental component of one period RMS)

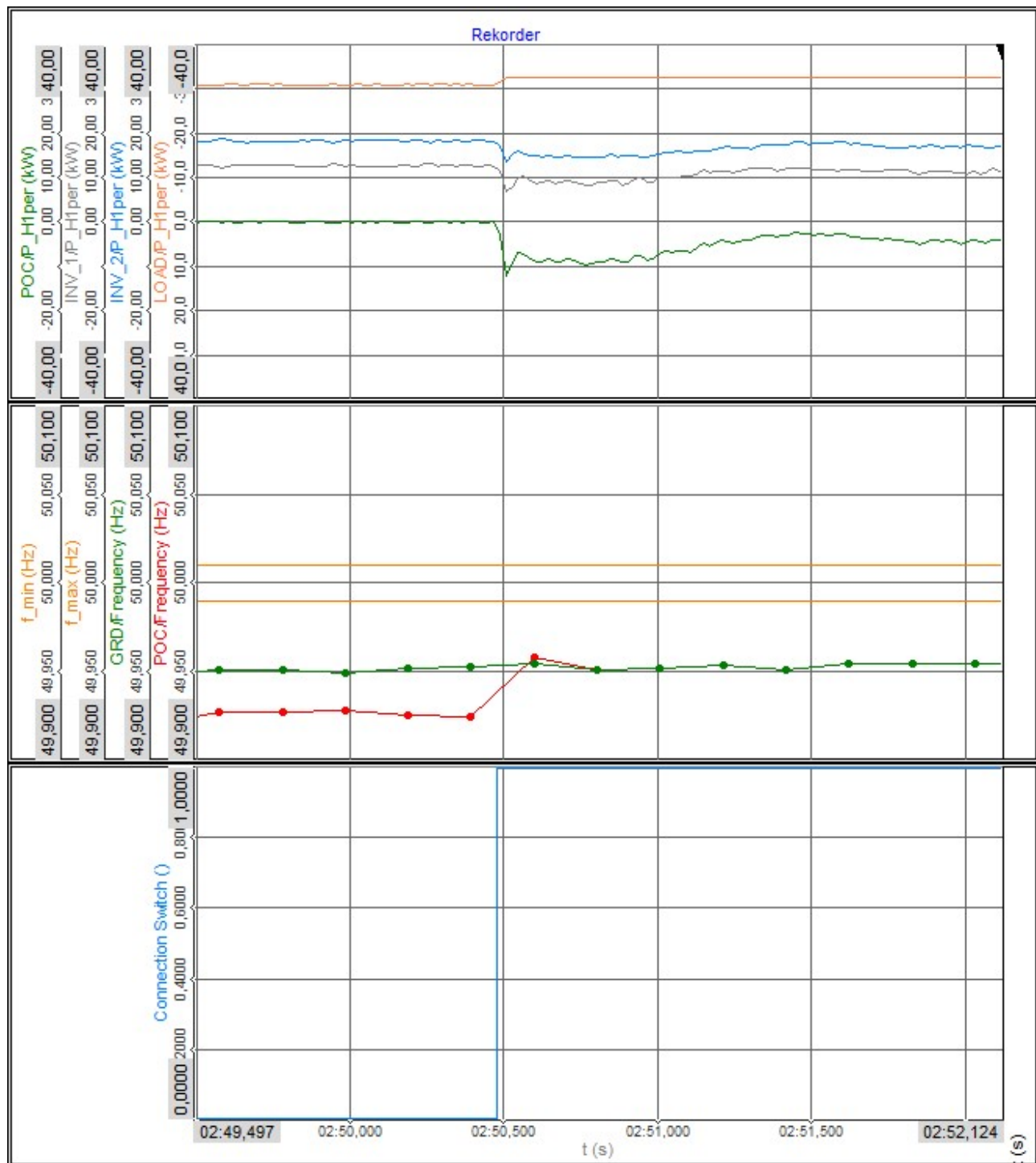


Figure 31: RC.T1 Reconnection Test 2.

LOAD/P_per: load power; INV_1/P_H1per, INV_2/P_H1per: active power of the first and second inverter; POC/Frequency: microgrid frequency; GRD/Frequency: utility grid frequency; f_{min} / f_{max} frequency tolerance band; POC/P_H1per: Active power at the POI; Connection switch: State of POI breaker (P_per: one period RMS; P_H1per: fundamental component of one period RMS)

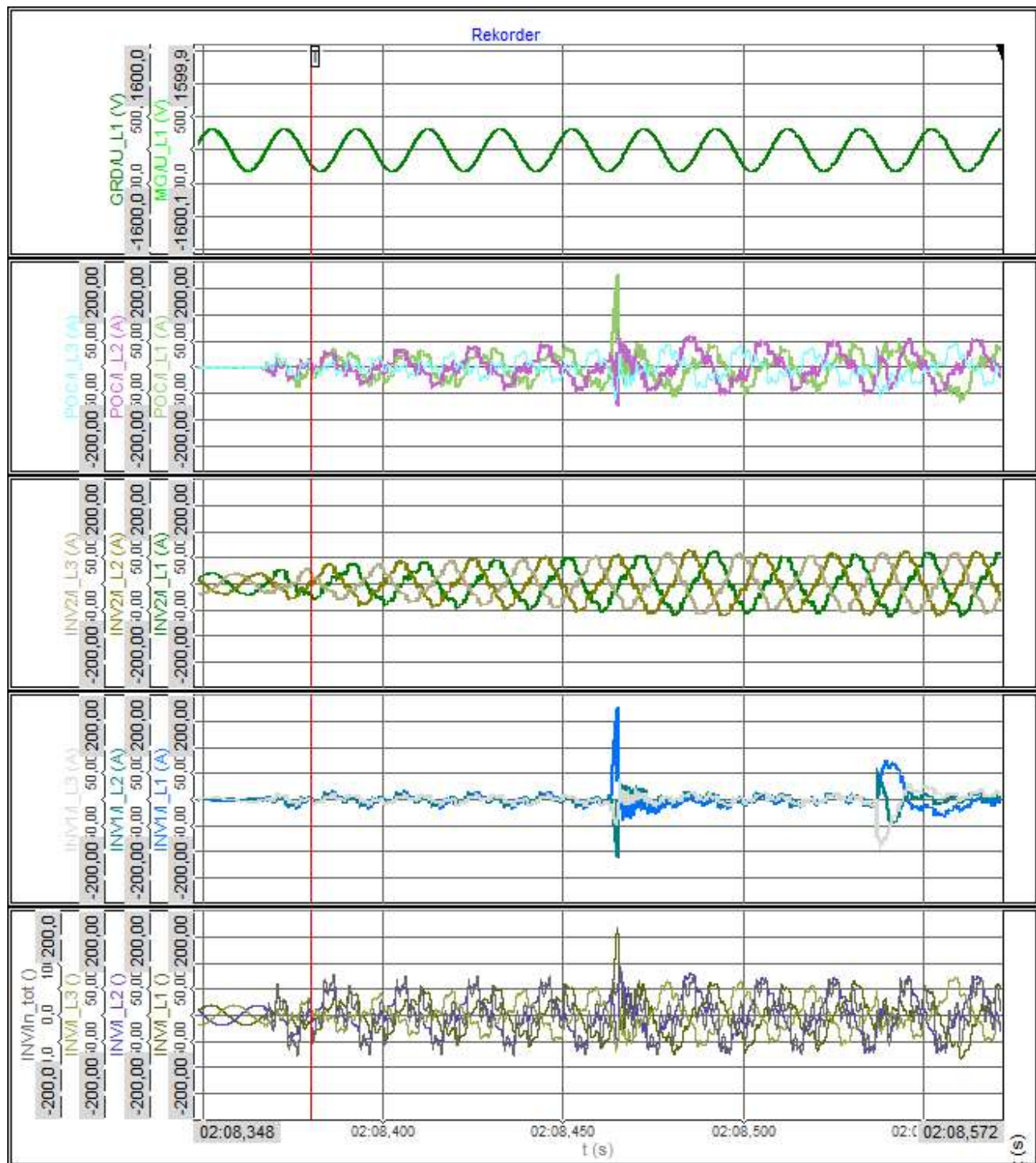


Figure 32: RC.T1 Reconnection – Transient behavior.

POC/L...: Phase currents at POI; INV_1,2/L... Phase currents of the inverters; INV/In_tot: current of inverter 1 and 2 in neutral line; GRD/U_L1: Grid voltage; MG/U_L1: Microgrid voltage)

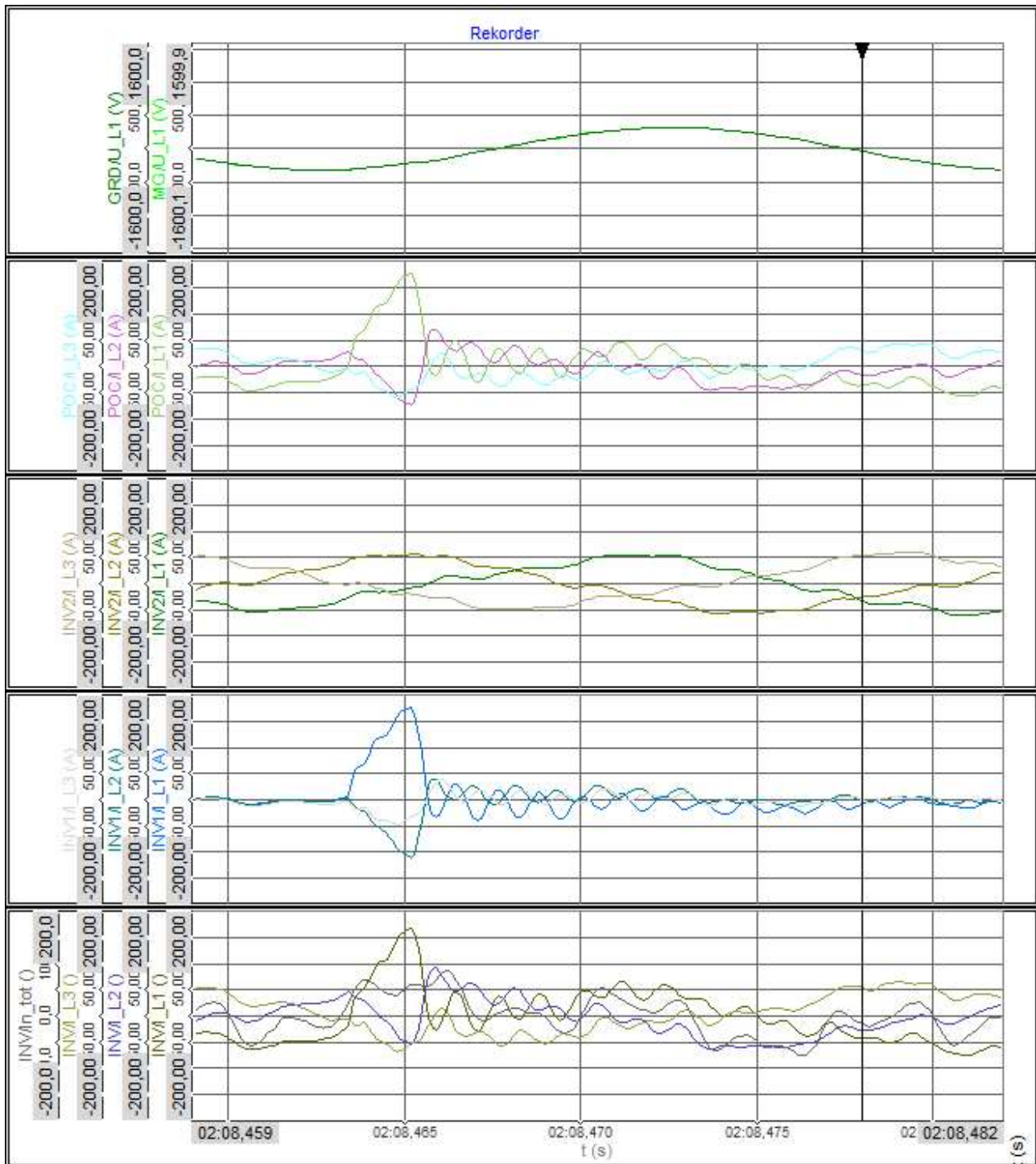


Figure 33: RC.T1 Reconnection – Detail Transient behavior - current peak 200A for 2ms at Phase 1.
 POC/I...: Phase currents at POI; INV_1,2/I... Phase currents of the inverters; INV/In_tot: current of inverter 1 and 2 in neutral line; GRD/U_L1: Grid voltage; MG/U_L1: Microgrid voltage)

5 Conclusions

The IEEE 2030.8 test methodology is used to reveal weaknesses of the microgrid control system. As each microgrid configuration is individual the test engineer needs to define specific test scenarios for its microgrid. Thus, the IEEE 2030.8 standard appears more as a guideline with the focus on field installations, than a step by step test procedure. It provides a basic test methodology to reveal critical issues for steady-state islanded, grid-connected as well as transition functions. For future versions of MGCS standards more detailed specifications and examples for test scenarios and applicable metrics would be useful:

- Improvement of the definitions for metrics as response and settling time. For the used variable e.g. in islanded mode, it is useful to use voltage or frequency instead of the power of the generator units. Holding times for load or DER output power steps must be defined to increase reproducibility of the results.
- The standard mentions “one quarter cycle sample time” in order to “derive quantities such as frequency, rms voltage, [...] power quality (voltage and current harmonic distortions [...])”. Our measurements showed, that a sample time of one quarter of a cycle will not give accurate RMS values or harmonic distortion values. In comparison, the German FGW TR3 “grid connection allowance and electrical characteristics” requires a sample rate ≥ 10 kHz.
- On the other hand, the standard suggests 100 ms minimum sample rate for continuous data collection. Storing only frequency, voltage, current, active and reactive power of just one bus (e.g. PoI) as a single precision float will result in 16 GB of raw data per year. Storing also harmonics will increase this number significantly. This amount of data is in our opinion too much and not practical for field devices.
- In future standards for MGCS testing a minimum set of detailed test specifications and step by step procedures, which are applicable for most microgrid configurations would be useful.
- Pass fail criteria as minor and major failures should be introduced in future MGCS standards.

The standard is not applicable for vendors of microgrid controllers to certify their product according to the standard for generic arbitrary microgrids. It is not possible to compare a MGCS product A with product B, as no standardized microgrid configuration exists. This is seen necessary for a performance comparison of different microgrid controllers. An introduction of a simple and uniform microgrid configuration, especially for a CHIL [11] implementations, seem to be a promising future approach for comparable results. Furthermore, this would allow definition of unique experiment specifications for maximum reproducibility of the tests. [1]

Within the MGCS-LTV Transnational Access at the laboratory infrastructure of TECNALIA test specifications and step-by-step test procedures for all IEEE 2030.8 test cases are generated following the holistic test specification templates developed in the ERIGrid project and adequate experiments performed. During this work weaknesses could be also found for the tested experimental microgrid setup, which was expected as the microgrid and its MGCS at TECNALIA were not designed and built to be connected to the utility grid, but rather, for demos at research sites. Hence, these “weaknesses” are immaterial for the system under test. As the tested microgrid is used only as an experimental platform, no contractual requirements with different parties are foreseen. For a real field installation some improvements with concerns to national grid-connection rules (anti-islanding, power quality, Q(U) control in grid-connected mode) would be necessary [1].

For the system tested in this work, the weaknesses were [1]:

- Missing anti-islanding functionality in case of grid outage.
- Transient short violation of the current limits and reverse power flows of the microgrid forming inverter after a DER trip.
- Improper function of the secondary control after a DER trip or unplanned islanding (no frequency recovery to 50 Hz).
- Steady-state of the desired power at the POI is not always achieved in grid connected mode.
- Experimental setup related issues, e.g. the DC source of the inverters tripped sometimes because of short reverse power flows.

6 Dissemination Planning

The results are presented at the European PVSEC 2019 in Marseille [1] and the CIGRE SEERC Conference in Vienna 2020.

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