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20/09/2022	v1.1	Krzysztof Chmielowiec, Aleks Piszczek, Lukas Topolski (AGH)	First version for AIT approval

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List of Abbreviations

CO	Project Coordinator
EC	European Commission
LA	Lab Access
UG	User Group
UP	User Project
P(U)	Power versus Voltage etc.
AIT	Austrian Institute of Technology
DSOs	Distribution System Operators
PV	Photovoltaic
UVRT	Under-Voltage Ride Through
OVRT	Over-Voltage Ride Through
LFSM-O	Limited Frequency Sensitive Mode – Overfrequency
ROCOF	Rate of Change of Frequency
ROCOV	Rate of Change of Voltage
R	Resistance
L	Inductance
C	Capacitance
Un	Nominal Voltage

Executive Summary

The aim of proposed research was to examine the methods and technologies for optimal control of electrical distribution low voltage (LV) networks with high density of renewable energy sources, focusing on the photovoltaic (PV) installations integration. The applicants have identified the following technical areas to improve the sustainable development of distribution grids to meet the current challenges of the energy transition:

A. PV installations capability for detection of unintentional islanding operation.

B. The ancillary services provided by individual PV inverters for voltage regulation, system protection and overall grid stability,

In the scope of this work, the ability to meet the above-mentioned challenges, eight PV inverters (commercial products available on the commercial European market) were verified, by numerous laboratory tests. The laboratory works were conducted in 09-13.05.2022 and 28.03.2022 in Smartest Laboratory of Austrian Institute of Technology (AIT).

As a result of the conducted research, the ability of the tested devices to detect unintentional island operation was demonstrated, and precise graphs and calculations were provided documenting the performance and duration from the appearance of island operation to switching off the inverters. Also, static characteristics, such us P(f), Q(U) and P(U) of a selected PV inverter are presented.

Due to the large amount of obtained measurement data, the report presents only selected, representative results that allow to define the most important conclusions from the conducted research. The collected measurement database covers a wider spectrum of PV inverters configurations.

1 Lab-Access User Project Information

1.1 Overview

Title: Photovoltaic Integration in Distributed Power Systems

Acronim: PVinPS

Host infrastructure: Smart Electricity Systems and Technologies Laboratory (AIT)

Access period: 09-13.05.2022 and 28.03.2022

User group members: Krzysztof Chmielowiec, Aleks Piszczek, Lukas Topolski

1.2 Research Motivation, Objectives, and Scope

The motivation for carrying out the above-mentioned research was the presently observed rapid increase in photovoltaic (PV) micro-installation connections to low-voltage networks in Eastern European countries, including Poland. This raises the questions if the PV inverters, widely available in EU market, fulfil the numerous technical requirements specified in European and national regulations as expected by local distribution system operators (DSOs) which nowadays are struggling with the effects of integrating renewables into the grid.

The objective of the presented study was to conduct laboratory comparative tests of widely available on the European market photovoltaic inverters from various manufacturers. Tests were done for compliance with the requirements set out in the NC RfG network code [1], PN-EN 50549-1:2019-02 [2] standard and internal regulations of distribution system operators [3]. All tested photovoltaic inverters were received directly from their manufacturers or local distributors.

The scope of the laboratory tests included correctness verification of:

a) the response of PV inverters to changes in the frequency of the supply voltage in accordance with the Limited Frequency Sensitive Mode – Overfrequency (LFSM-O),
b) the reactive and active power control modes including Q(U) and P(U),
c) the detection of unintentional islanding operation.

1.3 Structure of the Document

This document is organised as follows: Section 2 briefly outlines the state-of-the-art/state-of-technology that provides the basis of the realised Lab Access (LA) User Project (UP). Section 0 briefly outlines the performed experiments whereas Section 4 summarises the results and conclusions. Potential open issues and suggestions for improvements are discussed in Section 5.

2 State-of-the-Art/State-of-Technology

The photovoltaic inverter is the heart of any photovoltaic micro-installation responsible for the DC-AC conversion of current and voltage, therefore, many concerns are focused on its operation, because its design quality may have significant influence on the safety, performance and reliable operation of the power system and power quality at the point of common coupling in low-voltage networks. In order to ensure appropriate operation of photovoltaic inverters, in the point of view of distribution system operators, including limiting the phenomenon of increasing the RMS voltage caused by the generation of electrical energy, a number of requirements have been formulated for micro-installations, which are specified in the EU network code NC RfG [1], the standard PN-EN 50549-1:2019-02 [2] and the internal document of Polish DSOs [3].

All above-mentioned documents [1-3] for the proper operation of photovoltaic inverters requires many different modes that must be or should be implemented in the PV inverter controller, such as:

a. LFSM-O mode which requires active power decrease in response to a frequency increase above 50.2 Hz with the programmable droop set to 2% (must be implemented),
b. reactive power control mode such as Q(U) or cosφ(P) (must be implemented),
c. active power control mode P(U) which should be activated after the reactive power control mode reach its maximum (should be implemented),
d. islanding operation detection using passive or active methods, such as ROCOF (must be implemented),
e. UVRT (Under-Voltage Ride Through) and OVRT (Over-Voltage Ride Through) modes, which requires a PV inverter to have immunity to defined voltage-time characteristic of voltage dips and voltage swells (should be implemented for type A power generating modules).

Beside above-mentioned requirements, many different requirements, that can improve the operation of micro-installations in low-voltage networks, can be discussed. For example, reference [4] reviews and analyses existing voltage control methods to improve voltage regulation and to increase hosting capacity in low-voltage networks. The authors of the paper propose a coordinated voltage control method, where the local controllers of each PV inverter use reactive power control mode Q(U) and, if necessary, the active power curtailment P(U) based on the local voltage measurement and the predetermined settings calculated by the supervision control unit. Performed simulations showed that the advantage of this method is that the calculated reactive power and the active power droop settings allow a fair contribution of each PV inverter to the voltage regulation.

In reference [5], the authors review various reactive power control methods and propose a centralised reactive power management and coordination of modified reactive power control mode Q(U) for allocating the reactive power to PV systems. Performed simulations showed that the proposed method can regulate voltages better than the regulation based on non-centralised reactive power control using standard Q(U) characteristics.

In reference [6], the authors, in terms of the Horizon 2020 InterFlex project, conducted research on increasing micro-installation hosting capacity in low-voltage networks by activating reactive and active power control characteristics in PV inverters. The authors conducted theoretical and practical analysis in three selected low-voltage networks located in the Czech Republic. The obtained results showed that activating the abovementioned characteristics can increase hosting capacity from 20% to 60% depending on feeder electrical parameters and micro-installation placement along the feeder. The Czech Republic DSO plans to take action to implement control functions in its network code.

In reference [7], the authors propose a new passive islanding detection technique based on the rate of change of voltage (ROCOV) and the ratio of voltage and current magnitudes (VOI) in order to detect all kind of events and distinguish them from islanding conditions. The authors performed simulations of islanding events and non-islanding events, such as a single-phase or three-phase to ground fault, a sudden connection of loads and capacitor bank switching on. The obtained results showed that the proposed method can correctly distinguish islanding conditions from other events that can occur in the network. The authors also highlight that the proposed method can be easily implemented in PV inverters or in protection systems of distribution networks.

The authors of this technical report would like to highlight that there is a small and insufficient number of publications that describe and analyse practical research on requirements of PV inverters with accordance to the EU network code NC RfG [1] and the standard PN-EN 50549-1:2019-02 [2].

3 Executed Tests and Experiments

3.1 Test Plan, Standards, Procedures, and Methodology

3.1.1 Unintended islanding detection

According to the provisions of the PN-EN 62116 [8] standard, the state of unintentional island operation occurs when one or more distributed sources remain in operation after the power system is disconnected. Island operation detection is one of the obligatory conditions that must be met by distributed generation systems. Unintentional occurrence of island operation may pose a threat to consumers, be a source of poor energy quality parameters and may be a threat to the life and health of technical services.

The tests were carried out in terms of compliance with the requirements of applicable norms and standards. The standard includes verification methods for PV inverters, according to which tests should be performed for selected operating points defined by the volume of energy generation and the degree of imbalance of the circuit with active and reactive power. The research on the detection of unintentional island operation included the measurement of the shutdown time of PV inverters due to disconnecting the power grid.

Each PV inverter should automatically turn off in less than 2 seconds from the start of island operation. The disconnection time should be less than 500 ms if islanding detection is based on a frequency change measurement (ROCOF).

The standard PN-EN 62116 [8] indicates that only one inverter connected should always be tested, while as part of the tests carried out, it was decided to check the behaviour multiple inverters connected and operating in one electrical point.

3.1.2 Active power response to overfrequency

The required P(f) characteristic, as presented in the standard PN-EN 50549-1:2019-02 [2], with allowed operation area marked in purple is presented in Figure 1. This standard also defines the acceptable accuracy of active power reduction which is ±10% of the inverter rated active power (applicable only for frequencies above 50,2 Hz). The area defined by this accuracy is marked in green.

This mode of operation, abbreviated as LFSM-O, requires active power output reduction in response to an increase in the system frequency above a certain value. Photovoltaic inverters shall be capable of activating:

- active power response to overfrequency at a programmable frequency threshold above 50,2 Hz and up to 52 Hz,
- a programmable active power droop shall be in the range of at least 2% - 12% (default value s = 2%).

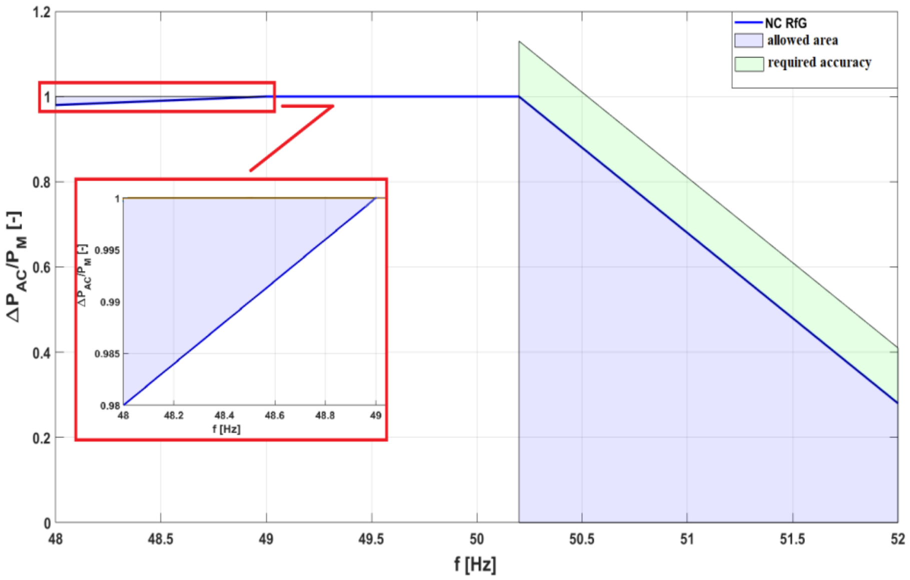

Figure 1: Permissible operating range of photovoltaic inverters in P(f) mode

3.1.3 Reactive power control in Q(U) mode

Photovoltaic inverters shall have the capability of managing reactive power in the wide range of normal operation. The reactive power control shall be within the displacement power factor cosφ ranging from 0.9ue (under-excited) to 0.9oe (over-excited), while actual generating active power P is greater or equal to 20% of the nominal photovoltaic inverter active power.

PV inverters shall be capable of operating in three reactive power control modes:

- constant cos(phi),
- constant reactive power,
- cos(phi) as a function of generated active power,
- Q(U) mode i.e., reactive power as a function of AC grid voltage.

In Q(U) mode PV inverters shall response to the RMS voltage changes and prevent from exceeding RMS voltage over permissible limits for the low-voltage network. Figure 2 presents the required Q(U) characteristic for 3-phase PV inverters, where: Q - reactive power at the output of the power generating module [var], P_D - maximum active power at the output of the power generating module at the phase shift factor between the symmetrical components of the positive sequence of voltage and current cosφ = 0,9.

According to PN-EN 50549-1:2019-02 [2] the reactive power (both inductive and capacitive) should be supplied by the PV inverter with an accuracy of ± 2% the maximum apparent power of the inverter. This accuracy is 5 times more demanding than in the LFSM-O mode.

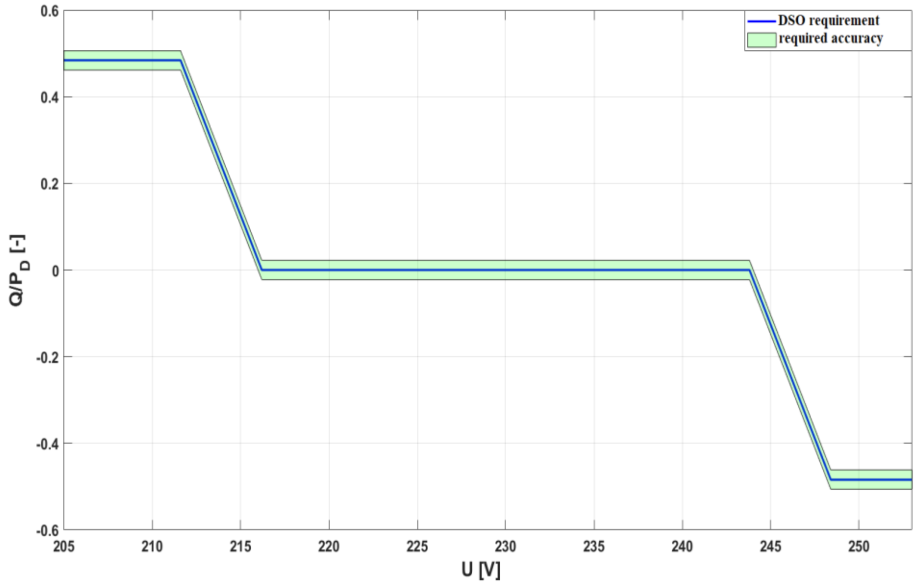

Figure 2: Required operation range of photovoltaic inverters in Q(U) mode

3.2 Test Set-up(s)

For each test of islanding detection 1, 2 or 3 inverters were powered by independent PV simulators and connected to the common power grid simulator. In the tested system, also passive, regulated energy receivers of R, L, C type were connected to adjust the active and reactive power balance of the testing circuit.

After the basic islanding test, different conditions on the AC side were created. With the use of the RLC load it was possible to create power unbalance conditions on the side of the grid simulator. Depending on the test, suitable unbalance of active and reactive power was created, either positive or negative.

Both 1- and 3-phase inverters were tested in configuration shown on Figure1. For 1-phase inverters the independent currents and voltages form both DC and AC sides were measured, the measurement was also made in point of common coupling. For 3-phase inverters only one phase of single inverters was measured, also in common point.

After the inverters were connected (i.e., when their power generation was stabilized), the grid simulator was disconnected and the voltage and current waveforms in the circuit were recorded by a built-in measuring system.

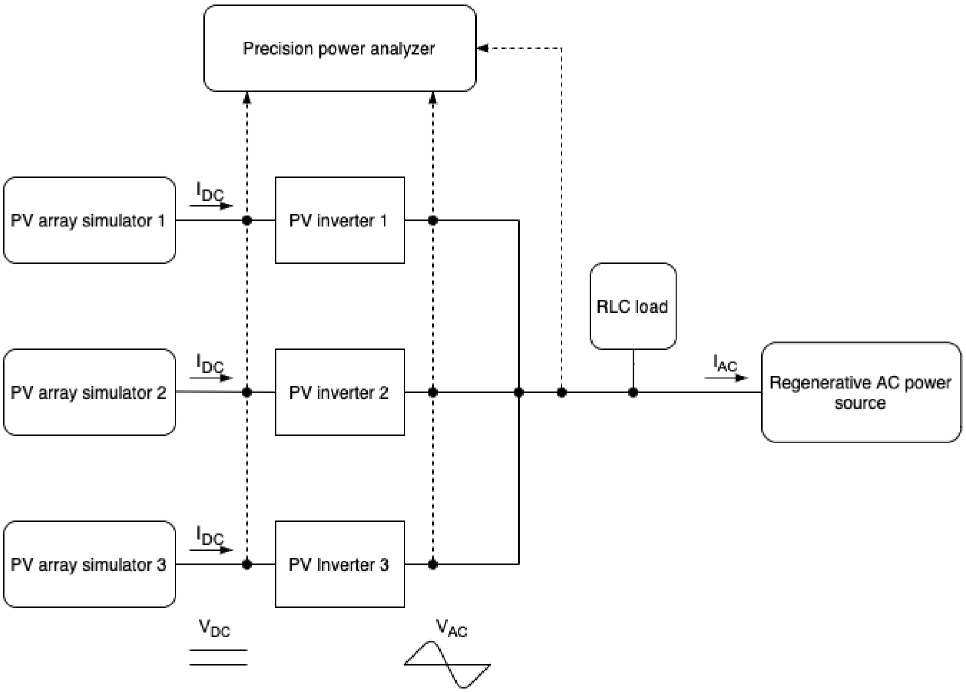

Figure 3: Block diagram of the stand for laboratory test of PV inverters

3.2.1 3-phase PV inverters islanding tests

In Table 1 and Figures 4-20 are presented results of the islanding tests of 3-phase PV inverters that were operating in different configurations and active power unbalance. The tests were conducted as follows. Firstly, all tested PV inverters were connected according to the test stand showed in Figure 3. Then, the test stand was energised and after the PV inverters reached steady state operation, the regenerative voltage source was switched off and the reaction (tripping time) of the tested PV inverters was observed. Each test was repeated few times to make sure that the results are comparable and to eliminate random reactions of the tested devices.

As it can be seen in Figures 4-12 where the results of the standalone PV inverters operation were presented, after switching off the regenerative voltage source all tested devices tripped off in the time up to 150 ms, except one test of the KOSTAL PV inverter, where its tripping time was 1.95 s (Fig. 6).

The next test was conducted on the standalone Twerd PV inverter, for which it was possible to activate the “off-grid” mode (turn off islanding detection). Figures 11-12 show that after activating the “off-grid” mode, the Kostal PV inverter was operating after switching off the regenerative voltage source.

The next tests were conducted on parallel operation of selected PV inverters, where in each test the Twerd PV inverter was operating with the activated “off-grid” mode. As it can be seen in Figure 13-18, despite that the Twerd PV inverter was operating in the “off-grid” mode, after switching off the regenerative voltage source, all tested PV inverters tripped off.

The last two tests were conducted with two PV inverters (where one of them was the Twerd PV inverter operating in the “off-grid” mode) where they were operating in active power unbalance conditions which were obtained by connecting a RLC load to the network. As it can be seen from Figure 19-20, despite of the Twerd PV inverter operation in the “off-grid” mode and the higher active power consumption than generation by 5%, all the tested PV inverters tripped off, but the big difference in the tripping time can be seen.

Table 1: 3-phase PV inverters islanding detection test results

Test no.	Inverter connected	Islanding detection on/off	P, Q unbalance	Islanding Detection time [s]
1.1	Kehua	On		0,15
1.2				0,15
1.3				0,15
1.4	Kostal	On		1,95
1.5				0,25
1.6	Solax	On		Inf
1.7				0,1
1.8				0,1
1.9	Twerd	Off		No detection
1.10				No detection
1.11	Solax, Twerd, Kehua	On, Off, On		0,4
1.12				0,45
1.13				0,55
1.14				0,45
1.15				0,25
1.16				
1.17	Kostal, Twerd, Growatt	On, Off, On	0, 0	1,2
1.18	Kehua, Twerd	On, Off	+5%P	0,1
1.19	Kostal, Twerd	On, Off	+5%P	2

Test 1.2 Single connected PV inverter Kehua

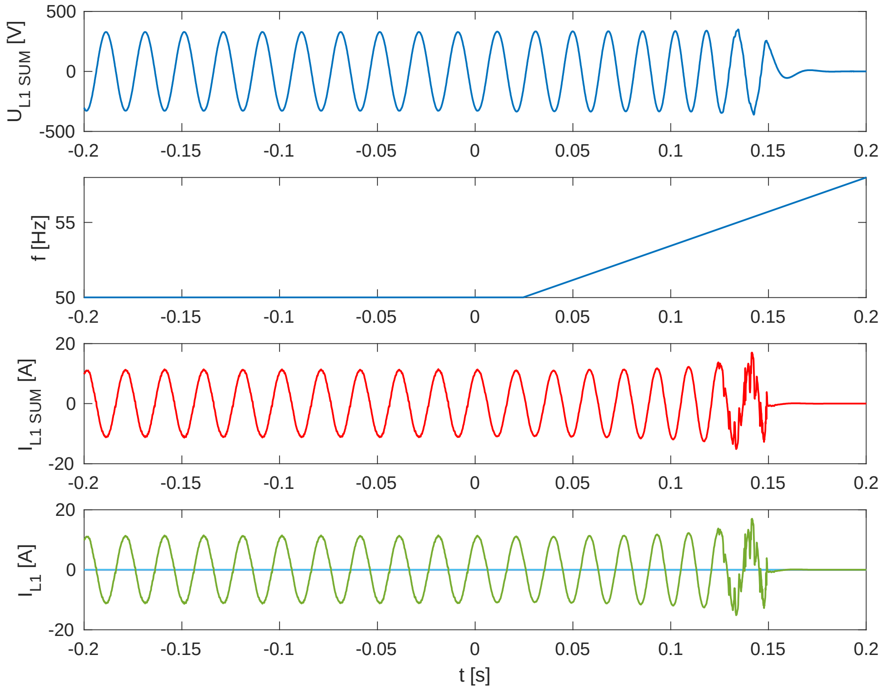

Figure 4: Kehua PV inverter islanding test 1.2 results

Test 1.3 Single connected PV inverter Kehua

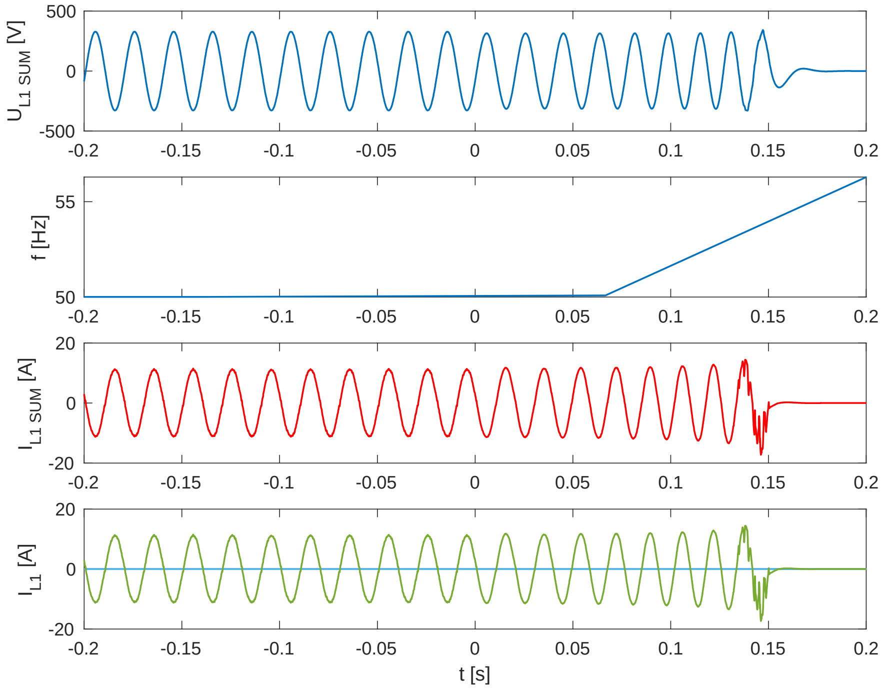

Figure 5: Kehua PV inverter islanding test 1.3 result

Test 1.4 Single connected PV inverter Kostal

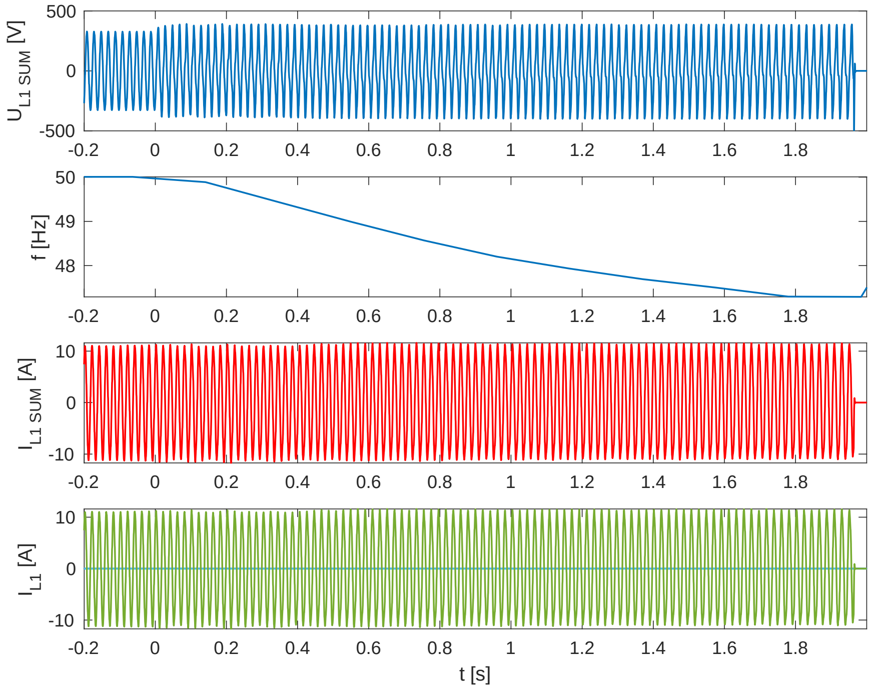

Figure 6: Kostal PV inverter islanding test 1.4 results

Test 1.5 Single connected PV inverter Kostal

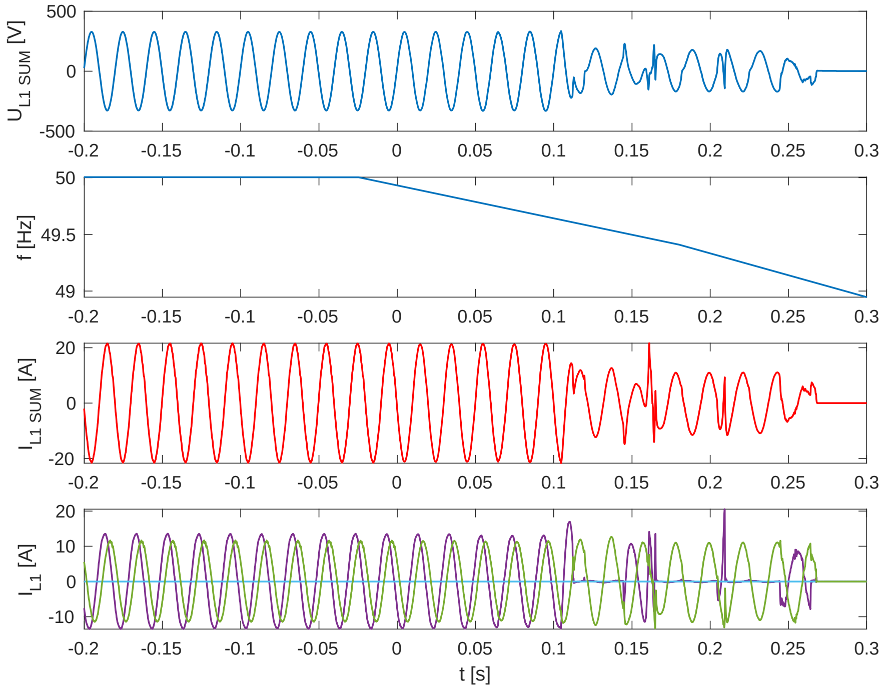

Figure 7: Kostal PV inverter islanding test 1.5 results

Test 1.6 Single connected PV inverter Solax

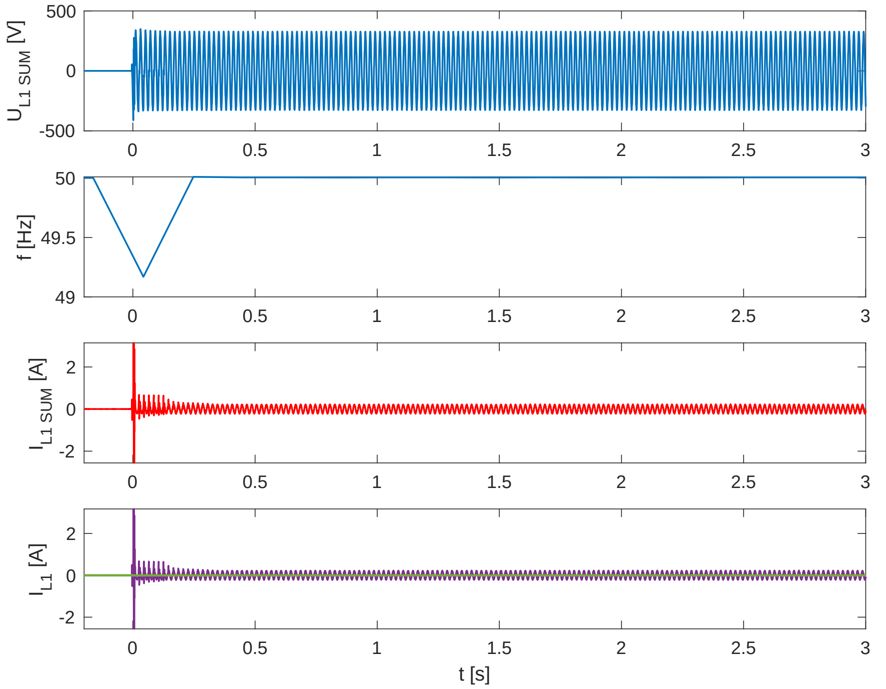

Figure 8: Solax PV inverter islanding test 1.6 results

Test 1.7 Single connected PV inverter Solax

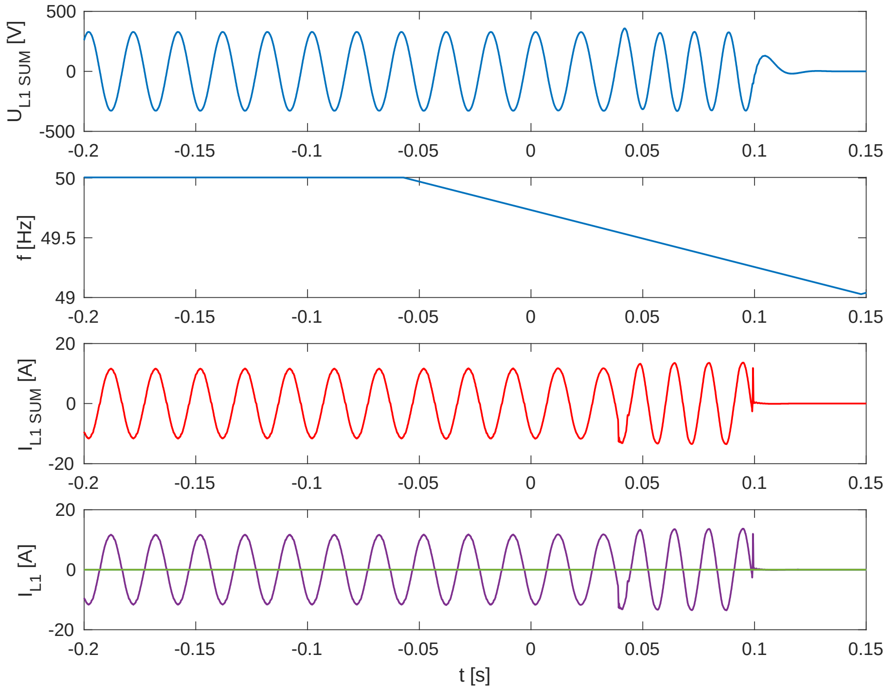

Figure 9: Solax PV inverter islanding test 1.7 results

Test 1.8 Single connected PV inverter Solax

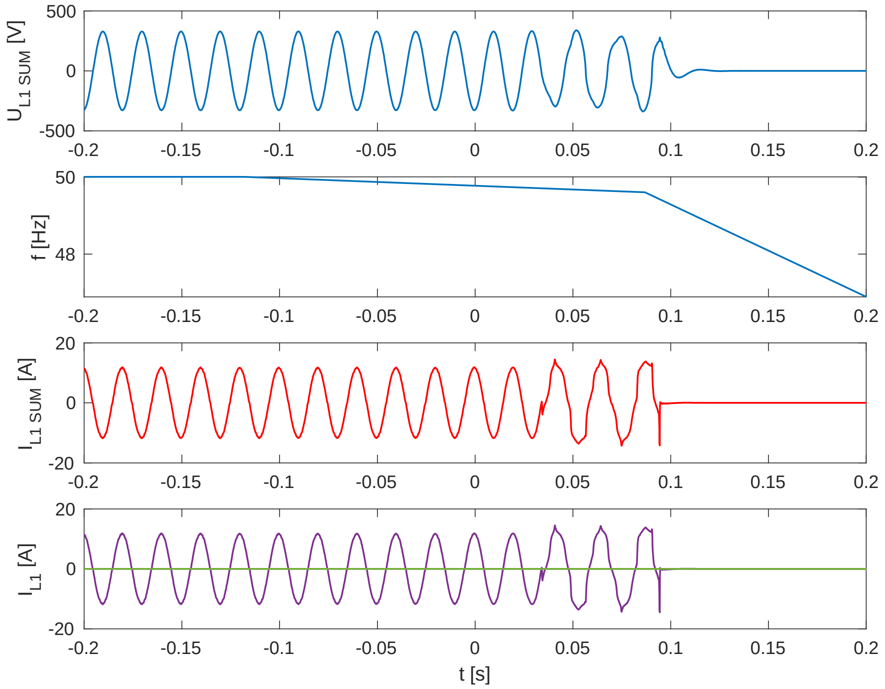

Figure 10: Solax PV inverter islanding test 1.8 results

Test 1.9 Single connected PV inverter Twerd

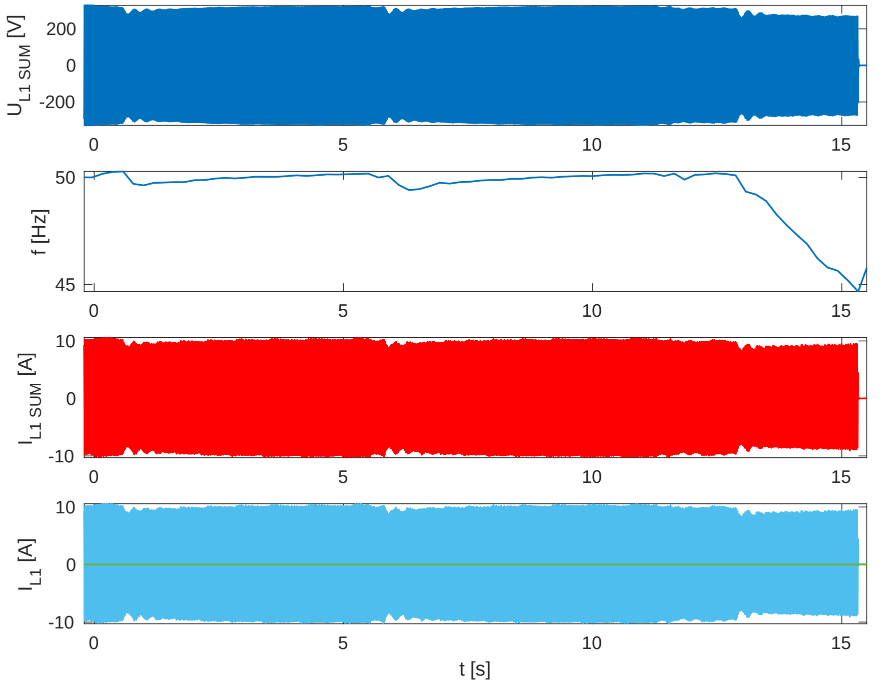

Figure 11: Twerd PV inverter islanding test 1.9 results

Test 1.10 Single connected PV inverter Twerd

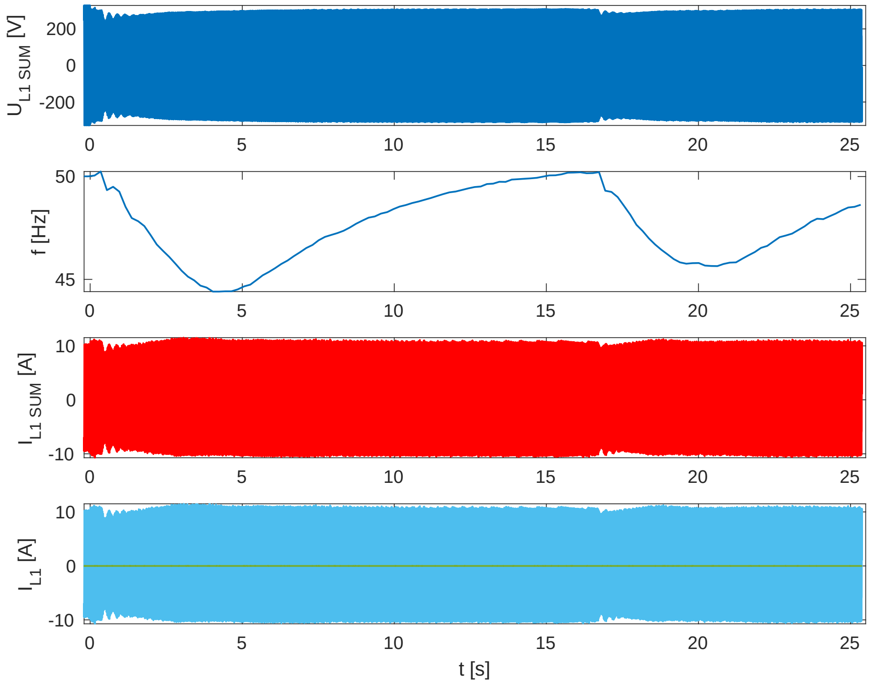

Figure 12: Twerd PV inverter islanding test 1.10 results

Test 1.11 Three connected PV inverters Solax+Twerd+Kehua

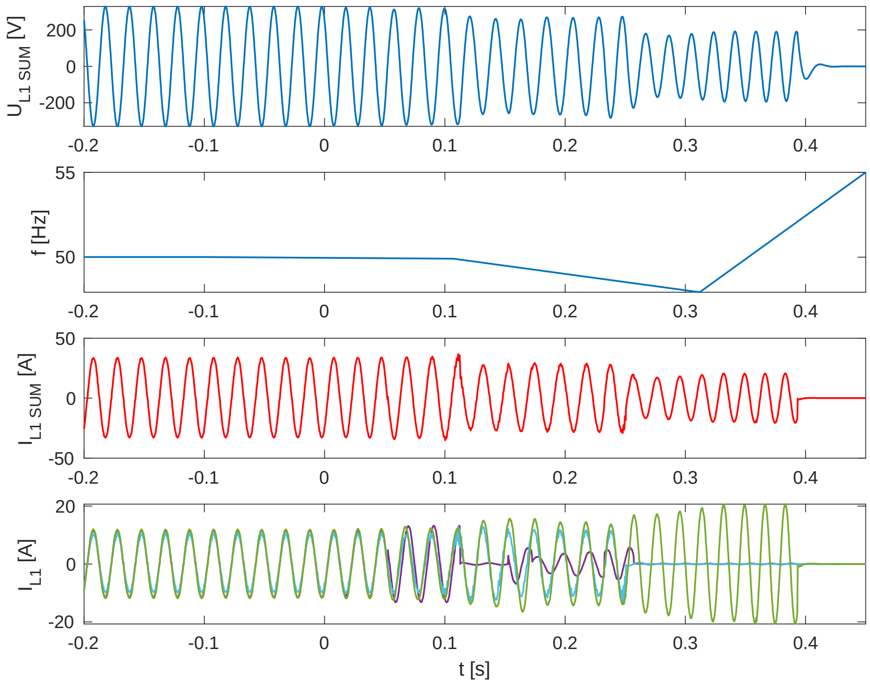

Figure 13: Solax, Twerd and Kehua PV inverters islanding test 1.11 results

Test 1.12 Three connected PV inverters Solax+Twerd+Kehua

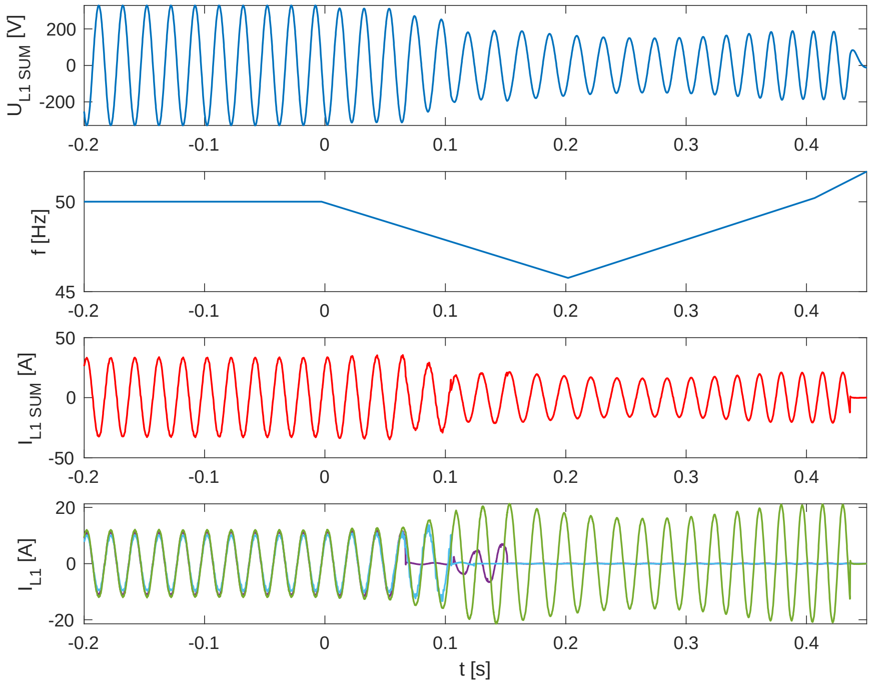

Figure 14: Solax, Twerd and Kehua PV inverters islanding test 1.12 results (Twerd PV inverter operating in “off-grid” mode)

Test 1.13 Three connected PV inverters Solax+Twerd+Kehua

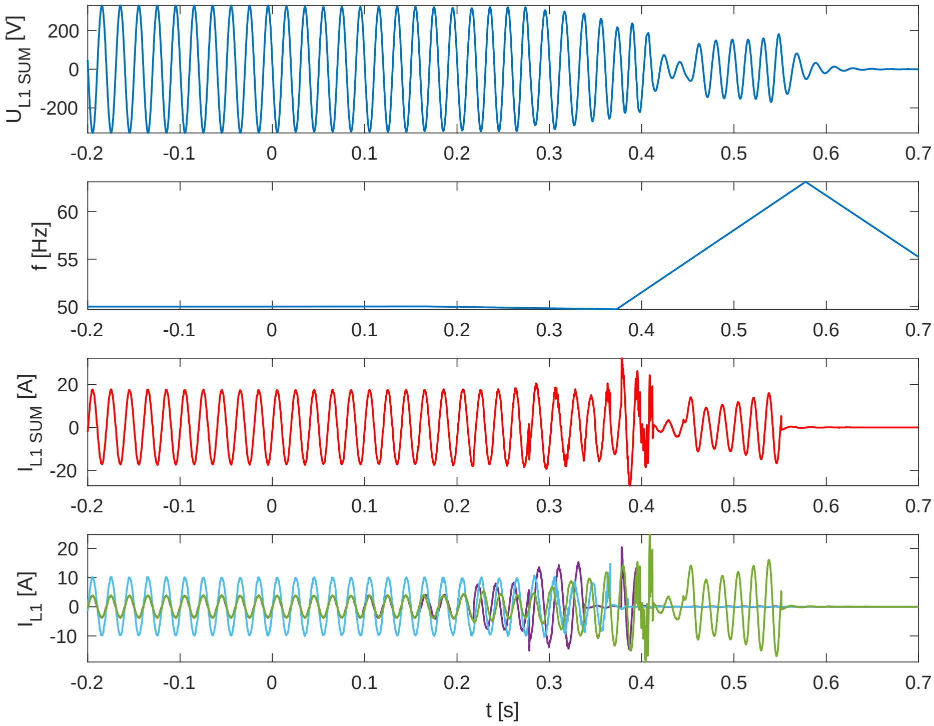

Figure 15: Solax, Twerd and Kehua PV inverters islanding test 1.13 results number 3 (Twerd PV inverter operating in “off-grid” mode)

Test 1.14 Three connected PV inverters Solax+Twerd+Kehua

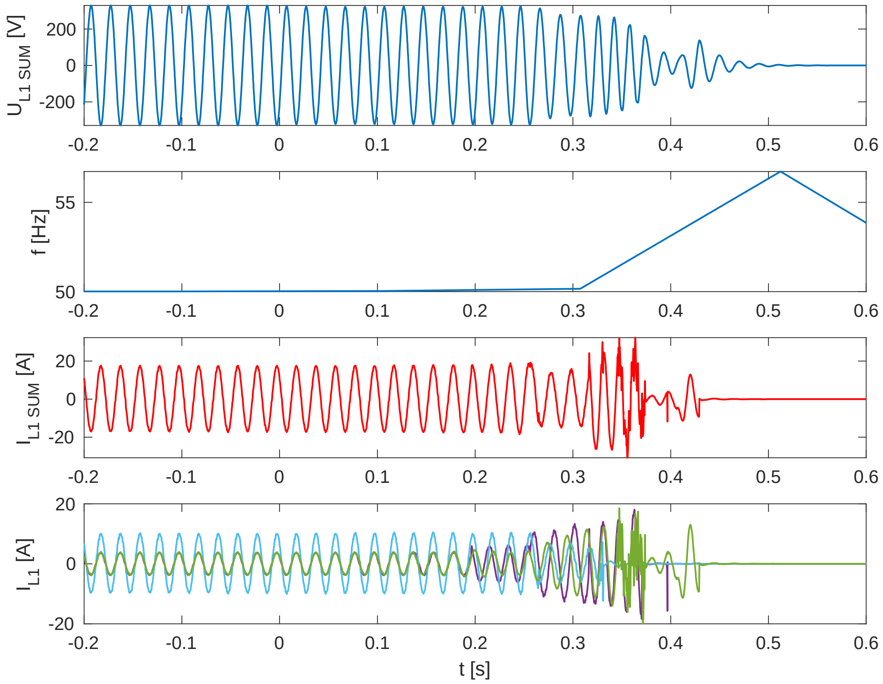

Figure 16: Solax, Twerd and Kehua PV inverters islanding test 1.14 results number 4 (Twerd PV inverter operating in "off-grid" mode)

Test 1.15 Three connected PV inverters Solax+Twerd+Kehua

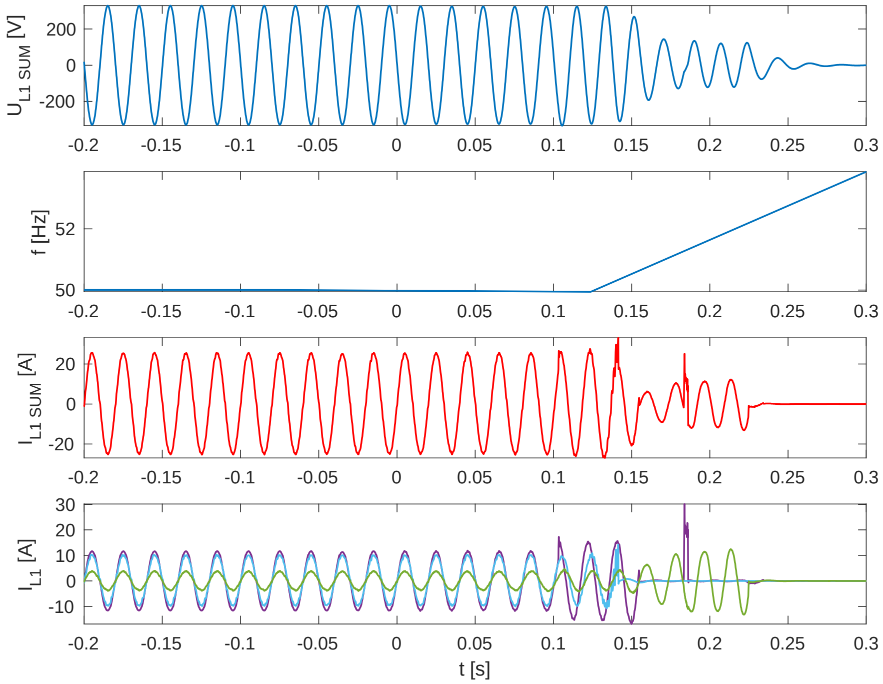

Figure 17: Solax, Twerd and Kehua PV inverters islanding test 1.15 results (Twerd PV inverter operating in "off-grid" mode)

Test 1.16 Three connected PV inverters Kostal+Twerd+Growatt

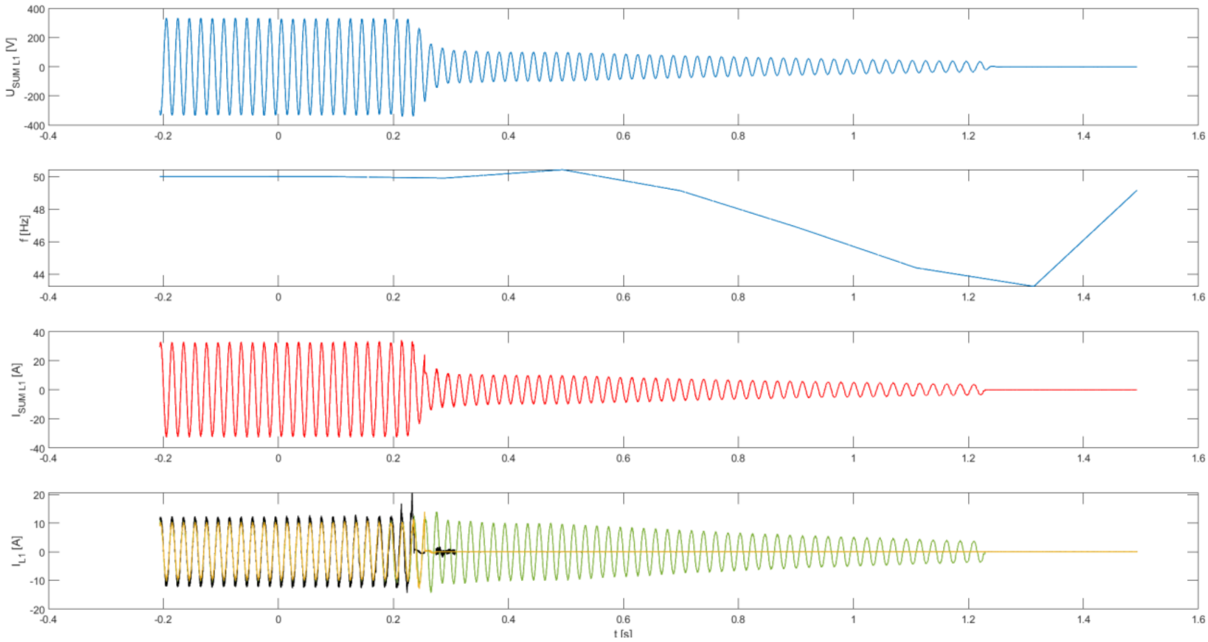

Figure 18: Kostal, Twerd and Growatt PV inverters islanding test 1.16 results (Twerd PV inverter operating in "off-grid" mode)

Test 1.17 Two connected PV inverters Kehua+Twerd

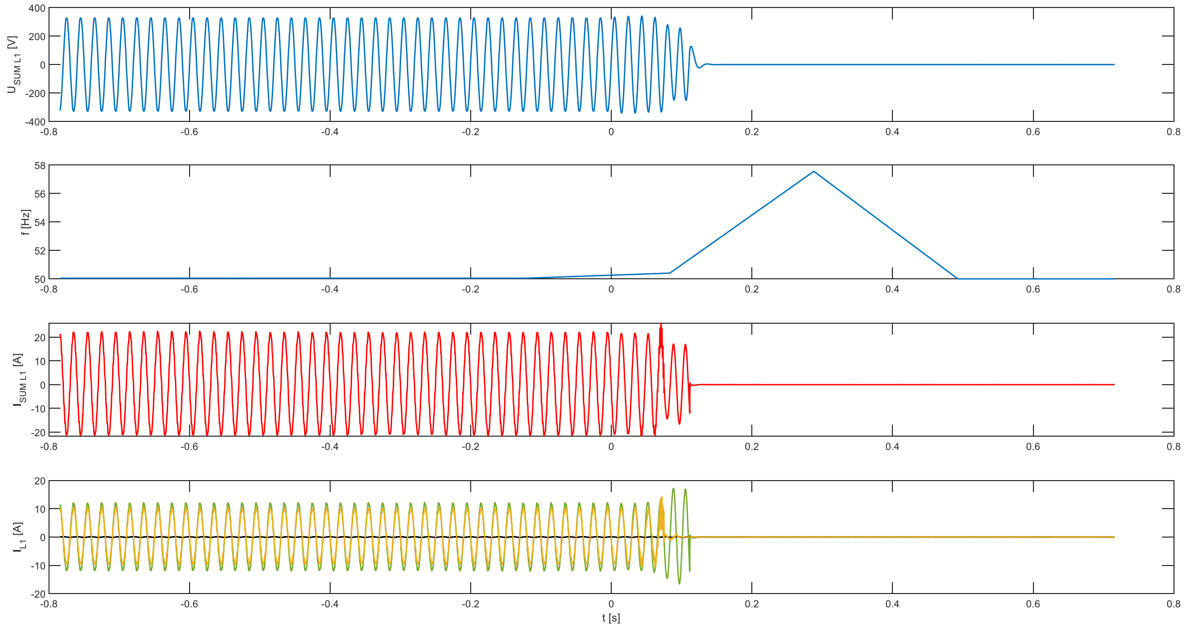

Figure 19: Kehua and Twerd PV inverters islanding test 1.17 results (Twerd PV inverter operating in "off-grid" mode)

Test 1.18 Two connected PV inverters Kostal+Twerd

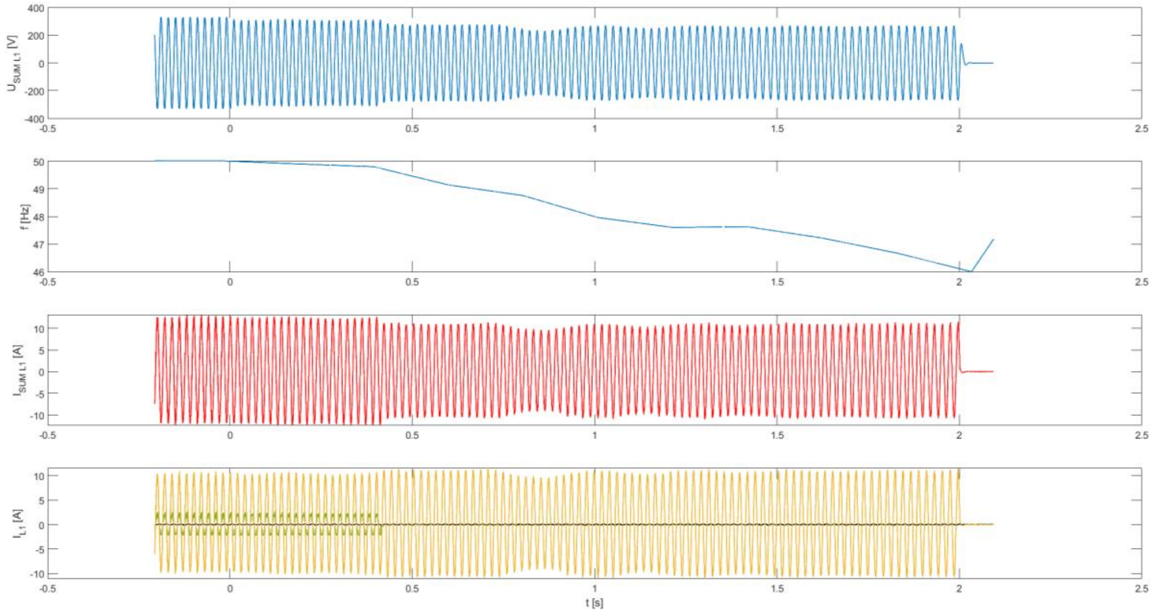

Figure 18: Kostal and Twerd PV inverters islanding test 1.18 results (Twerd PV inverter operating in “off-grid” mode)

3.2.2 Influence of load power unbalance on single 3-phase PV inverter operating in “off-grid” mode

The purpose of that test was to check the reaction of a selected PV inverter to the active and reactive power unbalance of the RLC load that was connected to the grid during islanding tests. The Twerd PV inverter operating in the “off-grid“ mode was selected.

As it can be seen in Table 2 and the Figures 21-26, the reaction of the Twerd PV inverter on the load RLC active and reactive power unbalance was different. When the load’s active and reactive power was balanced, the Twerd PV inverter was continuously operating in “off-grid” mode after disconnection of the regenerative voltage source (Fig. 21-22). When the load’s active power was smaller than the generated active power of the PV inverter, the Twerd PV inverter tripped off after disconnection of the regenerative voltage source (Fig. 23). The opposite reaction was observed when the load’s active power was higher than the generated active power. After the disconnection of the regenerative voltage source, the Twerd inverter was continuously operating in “off-grid” mode which can be seen in Figure 24. Similar situation was observed during load’s reactive power unbalance conditions tests. When in the system was too much inductive power, the Twerd PV inverter tripped off after disconnection of the regenerative voltage source (Fig. 25), but when in the system was too much capacitive reactive power, the Twerd PV inverter was continuously operating in the “off-grid” mode (Fig. 26).

Table 2: 3-phase Twerd PV inverter islanding detection test results in active and reactive power unbalance conditions

Test no.	Inverter connected	Islanding detection on/off	P, Q load unbalance	Detection time [s]
2.1	Twerd	off	0%Q, 0%P	No
2.2	Twerd	off	0%Q, 0%P	No
2.3	Twerd	off	-5%P	0,35
2.4	Twerd	off	+5%P	No
2.5	Twerd	off	+5%Q	0,3
2.6	Twerd	off	-5%Q	No

Test 2.1 Single connected PV inverters Twerd

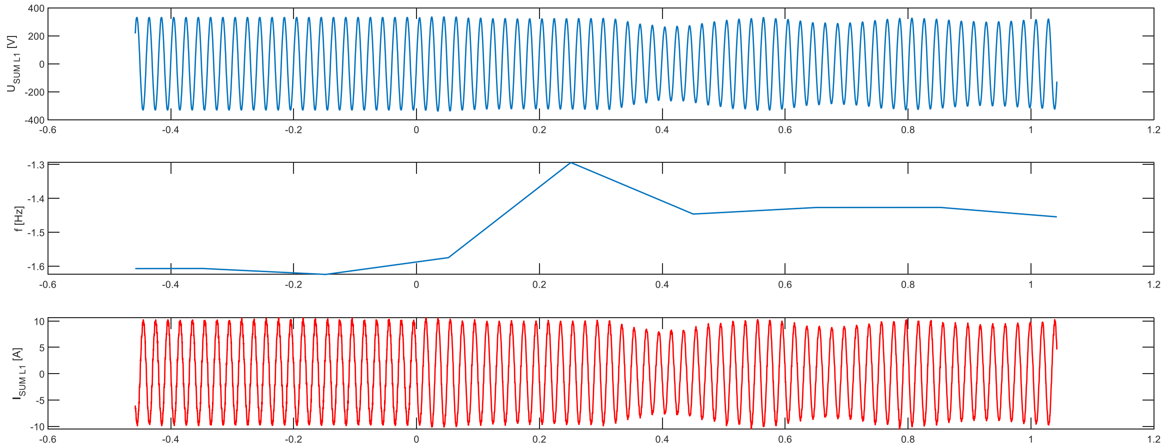

Figure 19: 3-phase Twerd PV inverter islanding test results in balanced conditions

Test 2.2 Single connected PV inverters Twerd

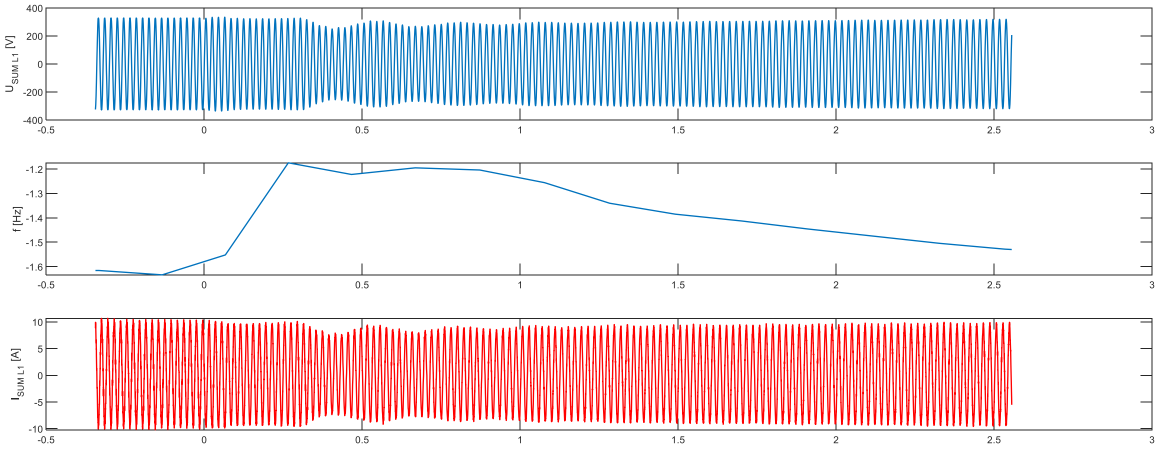

Figure 20: 3-phase Twerd PV inverter islanding test results in balanced conditions

Test 2.3 Single connected PV inverters Twerd

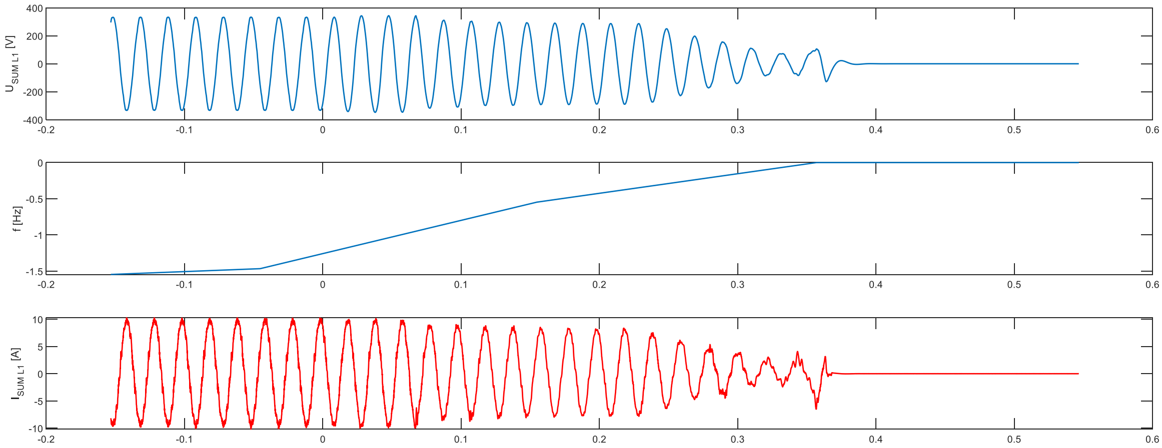

Figure 21: 3-phase Twerd PV inverter islanding test results in active power unbalance conditions (load active power was 5% lower that generated active power)

Test 2.4 Single connected PV inverters Twerd

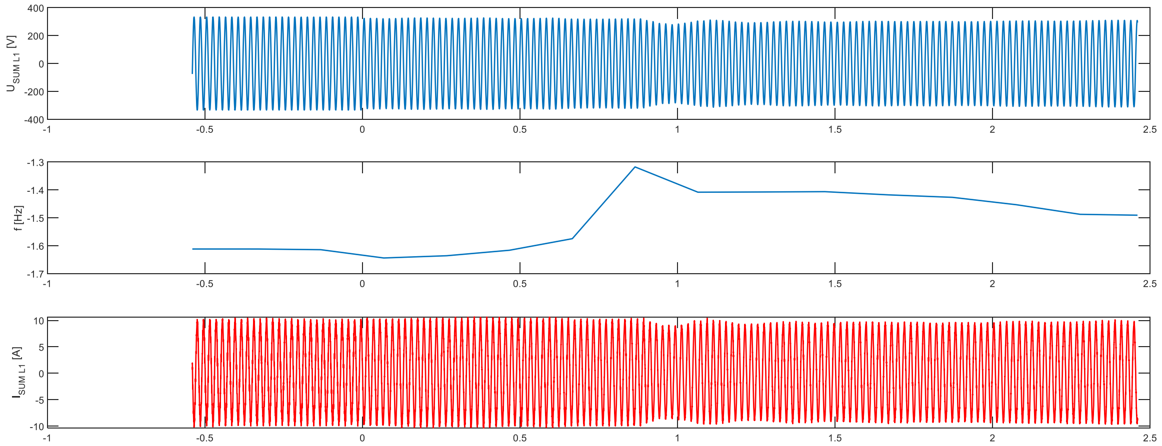

Figure 22: 3-phase Twerd PV inverter islanding test results in active power unbalance conditions (load active power was 5% higher that generated active power)

Test 2.5 Single connected PV inverters Twerd

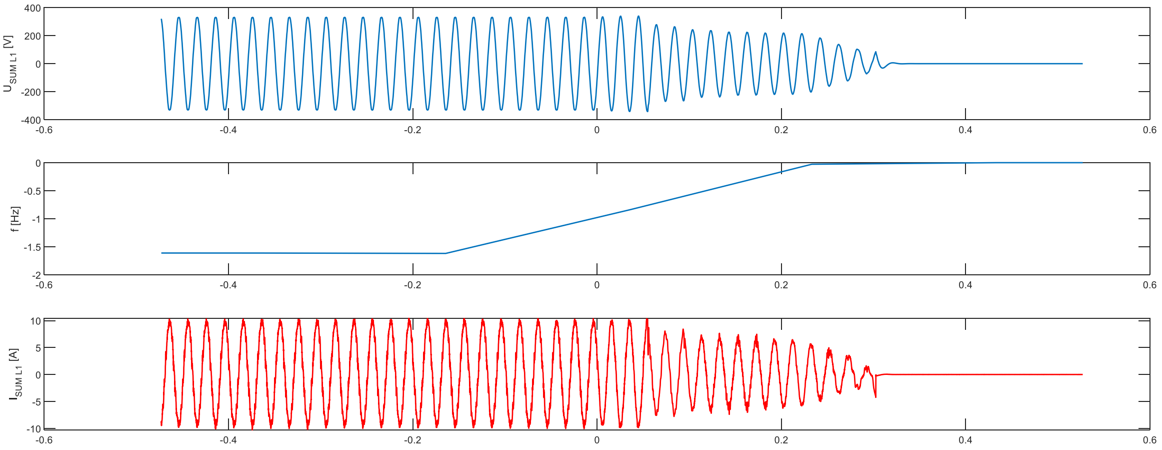

Figure 23: 3-phase Twerd PV inverter islanding test results in reactive power unbalance conditions (load inductive reactive power was higher by 5% than generated inductive reactive power)

Test 2.6 Single connected PV inverters Twerd

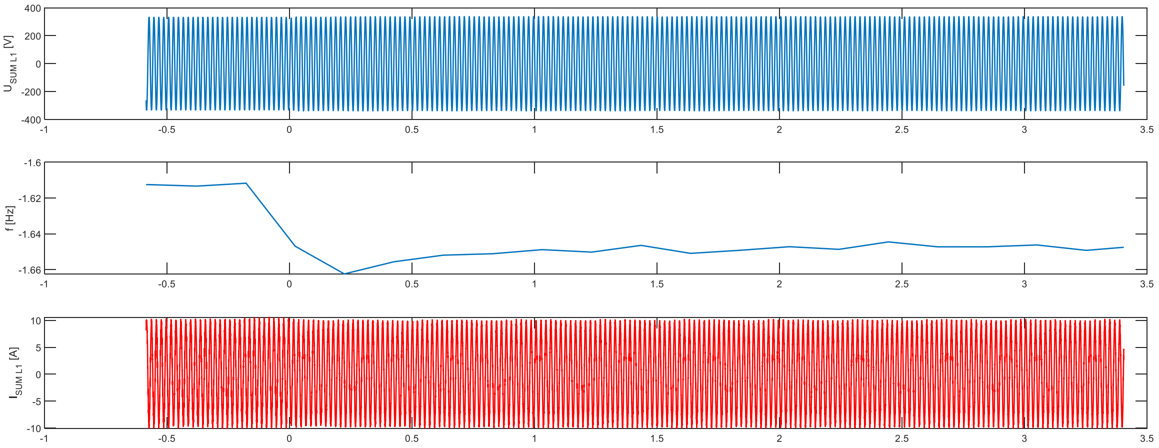

Figure 24: 3-phase Twerd PV inverter islanding test results in reactive power unbalance conditions (load capacitive reactive power was higher by 5% than generated capacitive reactive power)

3.2.3 1-phase PV inverters islanding tests

As for the islanding test of the 3-phase PV inverters, also 1-phase PV inverters was tested, for which the test results are presented in Table 3 and Figures 27-29.

Three tests were conducted on three 1-phase PV inverters operating in parallel with deactivated islanding detection mode. As it can be seen from the obtained results, after disconnection of the regenerative voltage source, all 1-phase PV inverters tripped off up to 1,7 s.

Table 3: 1-phase PV inverters islanding detection test results

Test no.	Inverter connected	Islanding detection on/off	P, Q unbalance	Detection time [s]
3.1	Kostal, Solis, Twerd	3x Off	No data	1,2
3.2	Kostal, Solis, Twerd	3x Off	No data	1,7
3.3	Kostal, Solis, Twerd	3x Off	No data	1,1

Test 3.1 Three connected PV inverters Kostal+Solis+Twerd

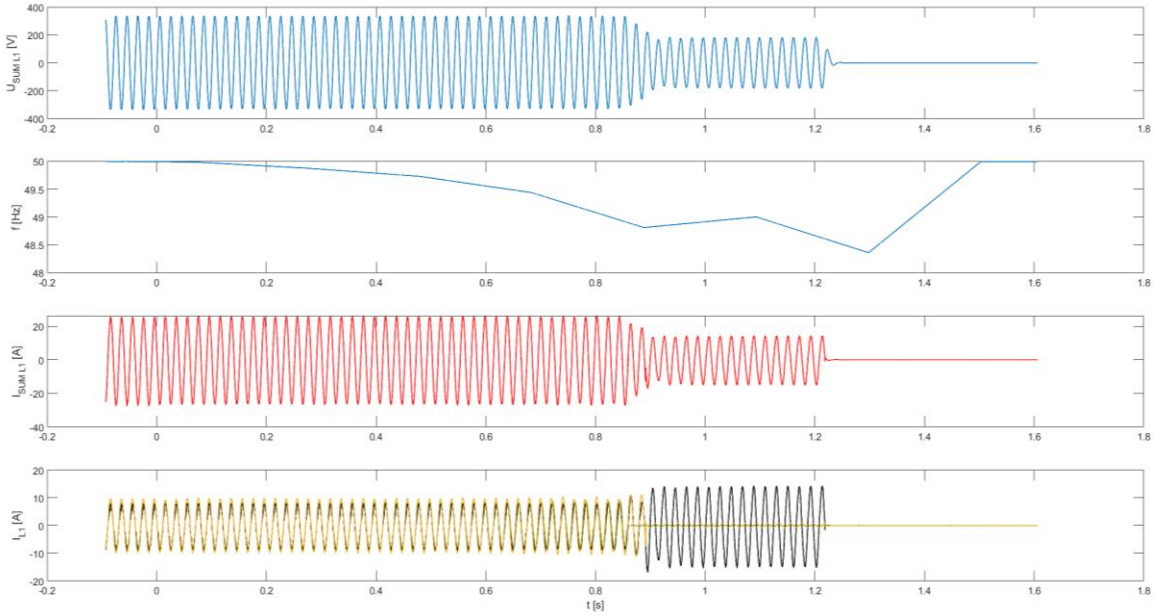

Figure 25: Islanding test results of the 1-phase Kostal, Solis and Twerd PV inverter

Test 3.2 Three connected PV inverters Kostal+Solis+Twerd

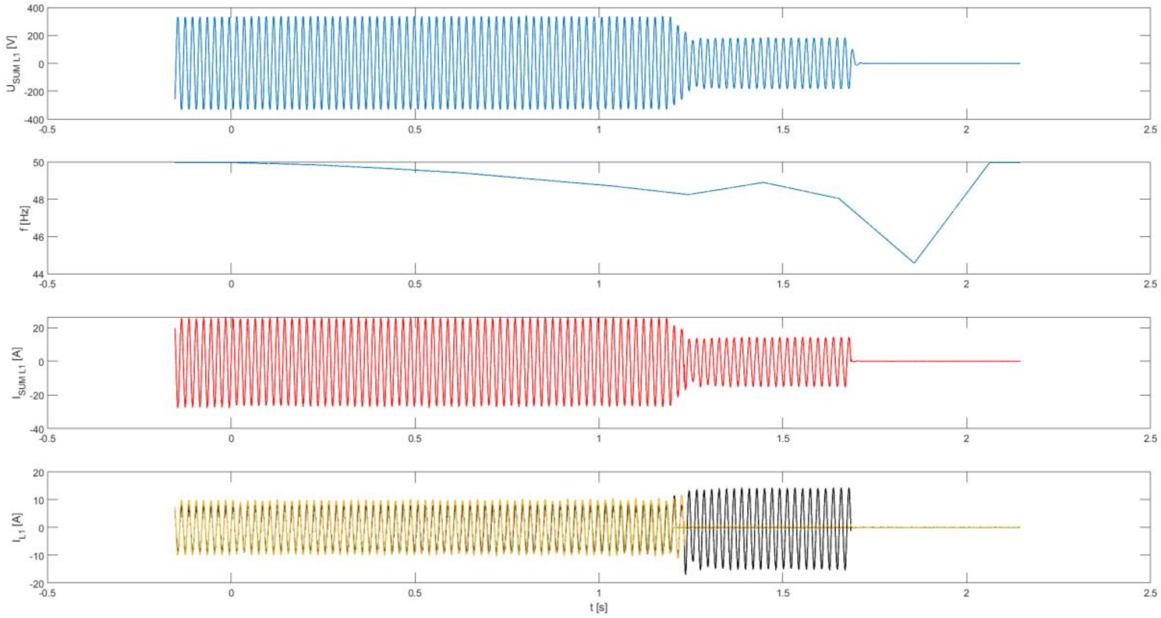

Figure 26: Second islanding test results of the 1-phase Kostal, Solis and Twerd PV inverter

Test 3.3 Three connected PV inverters Kostal+Solis+Twerd

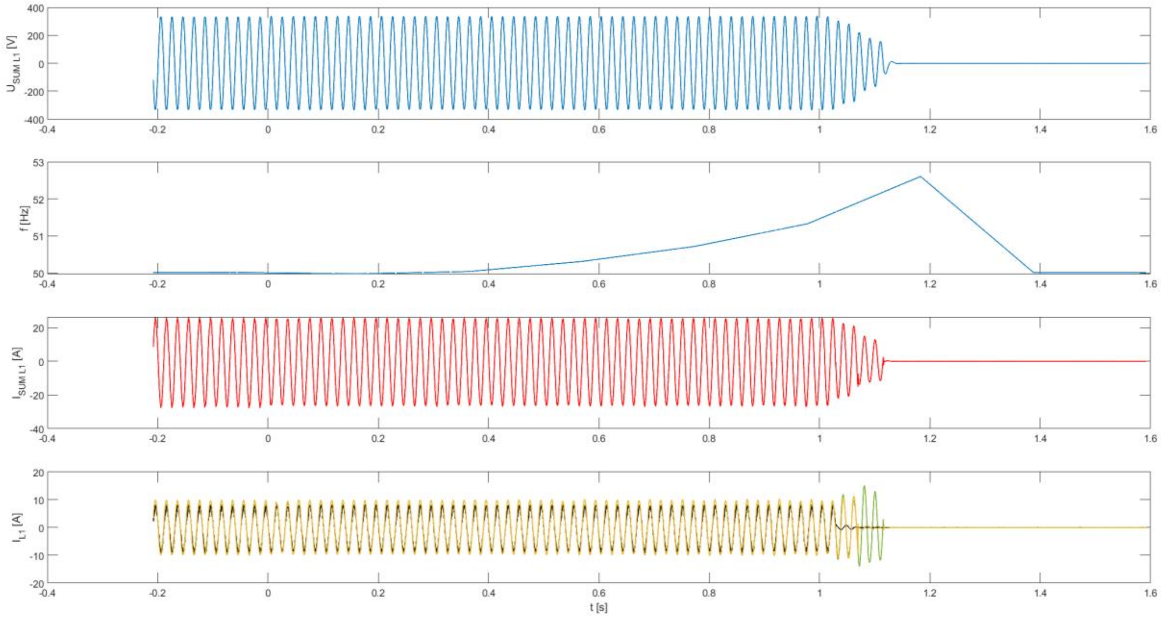

Figure 27: Third islanding test results of the 1-phase Kostal, Solis and Twerd PV inverter

3.2.4 Selected 3-phase PV inverter LFSM-O mode operation test

Beside the islanding tests of 1-phase and 3-phase PV inverters, also the test of the LFSM-O mode for the selected PV inverter was conducted. For the test the 3-phase Kostal PV inverter was chosen. As it can be seen in Figure 30, when the voltage frequency was increasing (above 50.2 Hz), the active power of the PV inverter was decreasing according to the required LFSM-O characteristic, with oscillations that in two points are beyond the required limit of ±10% of the nominal active power of the PV inverter defined in the standard PN-EN 505049-1:2019-02 [2].

3.2.1 Selected 3-phase PV inverter Q=f(U) mode operation test

Beside the LFSM-O mode operation, also the operation in Q(U) mode was tested for the 3-phase Kostal PV inverter. Before the test, required by the Polish DSOs Q(U) characteristic [3] was implemented in the Kostal PV inverter settings. As it can be seen in Figure 31, the tested PV inverter was correctly operating in the Q(U) mode, forcing the capacitive reactive power flow in low voltage conditions (below 0.94 Un) and forcing the inductive reactive power flow in high voltage periods (above 1,06 Un).

In Figure 31 can also be seen that the reactive power oscillations are beyond the strict requirement that is defined in the standard PN-EN 505049-1:2019-02 [2], which states that the static reactive power accuracy should not be higher than 2% of the maximal apparent power of the PV inverter (green area in Figure 31).

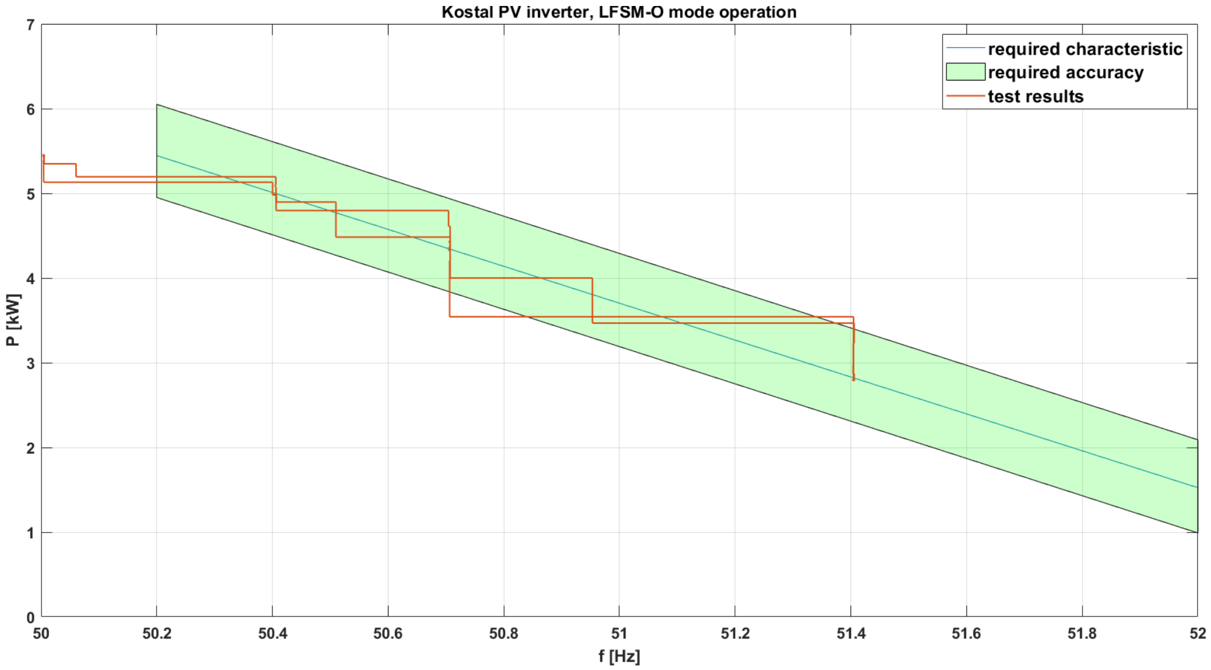

Figure 28: Kostal PV inverter operation in the LFSM-O mode

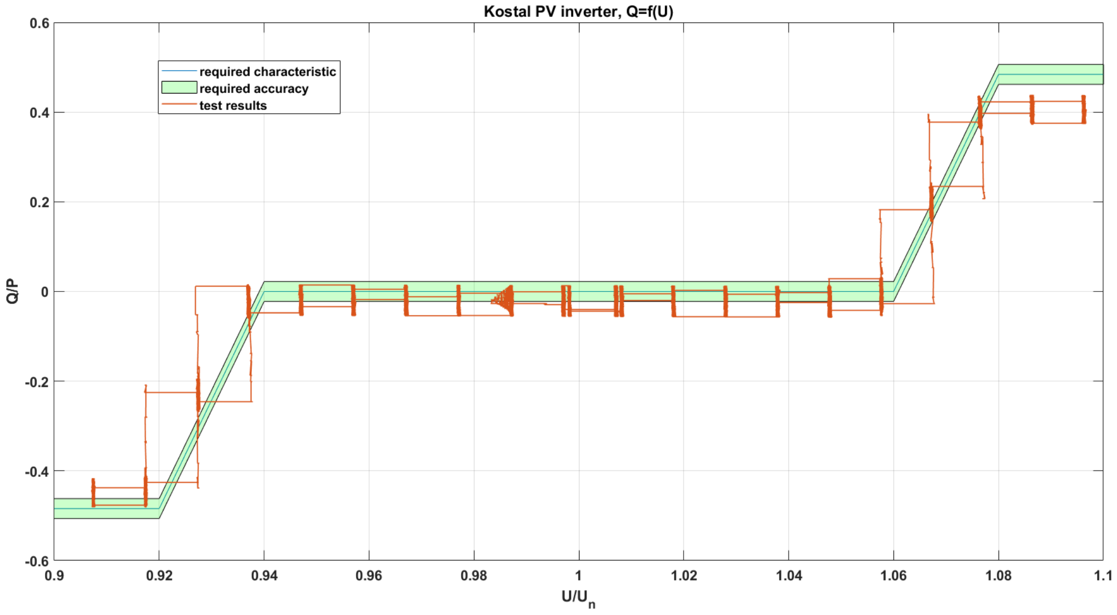

Figure 29: Kostal PV inverter operation in Q(U) mode

3.2.2 Selected 3-phase PV inverter P=f(U) mode test

The Kostal PV inverter was also tested for the operation in the P=f(U) mode. Before the test, the P(U) characteristic with a starting point of 248.4 V was implemented in the PV inverter. As it can be seen in Figure 32, when the voltage increased above 248.4 V, the PV inverter was decreasing the active power according to the pre-set P(U) characteristic. In Figure 32 can also be seen oscillations of the active power above 248.4 V, but the standard EN 505049-1:2019-02 [2] does not define the static accuracy or limits for the active power reduction in

P(U) mode operation.

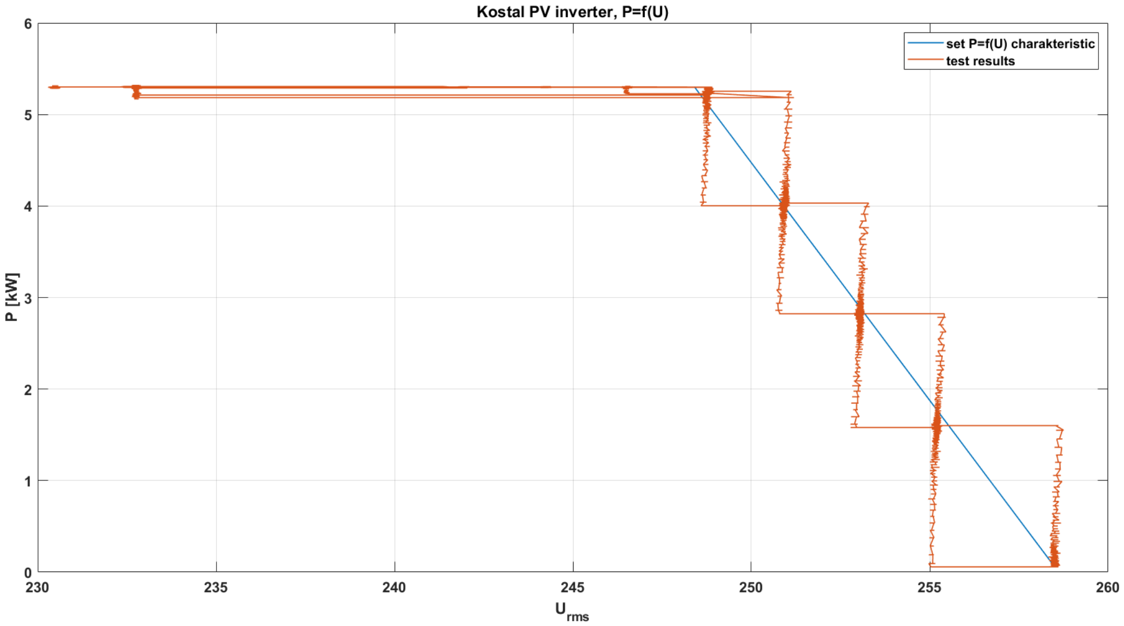

Figure 30: Kostal PV inverter operation in P(U) mode

3.3 Data Management and Processing

Measuring data – oscilloscope recordings of voltages and currents - was collected by laboratory built-in data acquisition system production of Dewetron.

Data was stored in *.CSV and *.DAT files and processed in Matlab/Scilab environment.

4 Results and Conclusions

Authors during two stays at AIT Smart Electricity Systems and Technologies Laboratory have conducted islanding tests and ancillary services provision tests of selected PV inverters, such as: LFSM-O operation, Q(U) and P(U) operation mode.

For the islanding test, five 3-phase and three 1-phase PV inverters were examined. The test results of the 3-phase PV inverters showed that whether the PV inverters were operating in active or reactive load power balance or unbalance conditions, as standalone or in parallel with activated or deactivated “off-grid” mode, after switching off the regenerative voltage source, all tested PV inverters were tripping off with different tripping time. Islanding operation was only observed for the standalone operation of the Twerd inverter in “off-grid” mode which was operating in active and reactive load power balanced conditions and when the load’s active power or capacitive reactive power was higher than the generated active and reactive power.

Similar situation was observed for the islanding test of the 1-phase PV inverters operating with deactivated “off-grid” mode. Whether the PV inverters were operating standalone or in parallel, after switching off the regenerative voltage source, all PV inverters were tripping off.

It can be concluded that the reaction of the testes 3-phase and 1-phase PV inverters to islanding conditions was correct and authors could not create conditions to prevent the PV inverters operating in parallel from tripping off.

For the 3-phase Kostal inverter ancillary services provision was tested, such as: LFSM-O, Q(U) and P(U) operation. The selected PV inverter was correctly operating in above-mentioned modes, but oscillations of active or reactive power are visible, where they sometime are beyond the required limits stated in standard PN-EN 505049-1:2019-02 [2].

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