# Towards Standardised Testing Procedures for Inertia Provision of Grid Forming Inverters

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**This paper (presentation file) was presented at the 21st Wind & Solar Integration Workshop and published in the workshop's proceedings.**

The workshop took place in The Hague, Netherlands and virtually on 12 – 14 October 2022.

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# Towards Standardised Testing Procedures for Inertia Provision of Grid Forming Inverters

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**Keywords**: GRID FORMING INVERTER, TESTING PROCEDURES, RATE OF CHANGE OF FREQUENCY (ROCOF) TEST, SYSTEM SPLIT TEST, INERTIA DETERMINATION

## Abstract

Grid Forming (GFM) Inverters and their capabilities are critical to enable growing penetration of Distributed Energy Resources (DER) into the electrical grid. The electrical inertia brought by GFM inverters to the network can replace or supplement the inertia of rotating machines that is a key element for power system stability. The German research project “Netzregelung 2.0” (“Grid Control 2.0”) investigated the operation of power systems with GFM inverters and developed inverter controls and possible grid code compliance testing approaches. First outcomes regarding the testing approaches for inertia provision are presented. A major portion of grid-forming control approaches can be described following the well-known equations of synchronous machines and thus can also be characterized in their frequency behaviour with reference to the first order swing equation of a rotating system, mainly characterized by the acceleration time constant (Ta) and damping (D). The accurate determination of these values is important for system operators and future ancillary service markets. Measurements were performed based on existing and upcoming standards and guidelines with a special focus on parameter determination and measurement uncertainty.

## 1 Introduction

With increased renewable energy penetration and the simultaneous disconnection of coal and nuclear power plants, power systems are transitioning from synchronous generators (SG) to inverter connected resources. Traditional power systems comprising large rotating masses contribute to the power system stability through their inertia.

Power system inertia, traditionally dominated by rotating masses, substantially influences the frequency response of the system to an imbalance between active power generation and load, either in an interconnected grid or following a system split event. During a system frequency change resulting from a power imbalance, the rotating masses of synchronous machines (SM) accelerate or decelerate and therefore absorb or inject electrical energy into or from the grid in order to compensate for the frequency deviation [1].

Conventional inverter interfaced resources operating in grid supporting or grid following mode do not contribute to power system inertia because their control is not able to adjust the active power contribution instantaneously. These inverters, behaving like current sources are called grid following (GFL) inverters. GFM inverters can provide a reliable alternative since they are acting as voltage sources and react instantaneously to changes of voltage and frequency, providing so-called electrical inertia. In addition to grid support during disturbance events, they are necessary for islanded operation and blackstart services [2]. The following Table 1 provides a comparison of GFM and GFL inverter capabilities:

Table 1: Comparison of GFM and GFL inverter capabilities

| Grid Forming Inverter | Grid Following Inverter |
|---|---|
| Voltage source inverter | Current source inverter |
| Controlling the voltage amplitude and system frequency | Adjusting voltage and frequency of the grid |
| Contribution to system inertia | - |

In their current network development plans the German and European Transmission System Operators (TSO) assume that there will be a shortage of system inertia provided by rotating masses in the near future, at least temporarily. They see the provision of inertia by DER with grid-forming capability as one of the pillars of the mitigation measures [3], [4].

A definition of a grid forming power plant or power park module, here GFM inverter, is provided in [5] as one that is capable of supporting AC power system operation (from extra high voltage (EHV) to low voltage (LV) level) without having to rely on capabilities from SG in normal distributed and emergency states. A key capability is ensuring stable operation in the extreme operating case of supplying the complete demand using 100% converter based resources [5].

For the secure operation of power systems, compliance assessment tests have to be performed for validation of the GFM inverter behaviour to ensure its reliable operation. Various project committees and working groups are working towards standardising the requirements on and behaviour of GFM inverters [6], [7]. One such systematic characterisation is presented in Fig 1 [7].

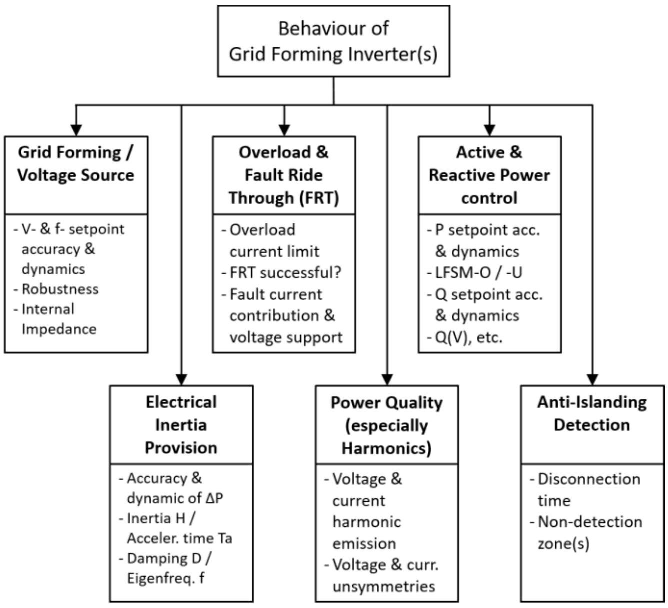


*Fig. 1 Characteristics of Grid Forming (GFM) Inverters [7]*

Synchronous inertia in a traditional power system acts in a short time frame ranging from milliseconds to seconds, which influences the frequency stability and the short-term stability. The inertial response of the GFM inverter primarily influences the dynamic response in reaction to a phase angle or frequency change wherein no change in the internal voltage magnitude of the source takes place.

A number of different GFM control methods exist [8], therefore tests on a GFM inverter should be performed with consideration of the GFM as a black-box such that the tests are independent of the control method. Inertia tests and their evaluation for the GFM inverter are explained in various literature.

In [9] it is emphasised that it is advantageous to parameterise the internal behaviour of the GFM inverter according to the swing equation of the synchronous machine through the inertia constant H and the damping factor D. Since the significance and meaning of these parameters is well known in the industry, the inertial behaviour of the GFM inverter can be adapted easily to existing grid operation concepts. Often the acceleration time constant (Ta) is used instead of the inertia constant. The inertia constant H is related to the acceleration time constant Ta according to Equation 1.

$$Ta = 2 * H \tag{1}$$

In a SM, the damping factor D impacts the rotor swings in case of a frequency event and thus impacts the rotor angle stability. It is necessary that the GFM inverter provide a damping similar to the damping torque of a SM. The swing equation transfer function representation is presented in Fig 2.

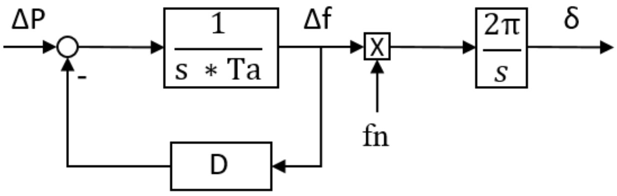


*Fig. 2 Representation of the swing equation of the synchronous machine*

[9] also discusses the validity of an equivalent second order synchronous machine model for representing GFM behaviour. In the suggested time domain method, comparisons are conducted between a detailed GFM inverter model and the equivalent second order model with approximated H and D parameters. This validation approach does not take into consideration laboratory tests with an actual GFM inverter wherein the results could be influenced by the test environment. The frequency domain method depicts laboratory applicability. However, it needs a lot of measurements. The frequency ramp method shows large error deviations for the verification of the parameters. All the methods in [9] depict the GFM inverter as having the second order swing equation characteristic of an SM influencing its inertia response. However as displayed in the frequency ramp method, a GFM device could have additional control loops which influence its dynamic response.

In [10], a distinction is made between transient inertia and medium term inertia behaviour of the GFM inverter. For calculating the transient inertia, a phase jump is performed at the terminals of the inverter and the H and D parameters in the second order equivalent model are adjusted to match the resulting waveform from a phase jump. The accuracy of the results from this fitting technique is not proven. For determining the medium term inertia, a system split test is conducted to create a slow frequency ramp during which the medium term inertia is calculated. But this reference does not provide any detailed test procedure for a laboratory experiment considering a system split scenario.

In [11], a Rate of Change of Frequency (RoCoF) test and a system split test method are described and laboratory experimental results are presented. The ROCOF test proposes deactivating the damping factor D in the GFM inverter internal mechanism for determining the Ta parameter with a frequency ramp simulated at the grid simulator. Additionally the system split test provides guidelines on determining both the H and D parameters, however the reproducibility of this test is not clarified.

### *1.1 Repeatability and Reproducibility*

Repeatability is a measure of probability that, having determined one result from an experiment, if the experiment is performed several times it would lead to the exact same result. It is the consistency with which an observer measures a set of

objects [12]. The test approaches for validation of the GFM inverter inertia parameters described above do not show enough repeatability in the results. In some cases the test description did not provide enough information for ensuring repeatability.
Reproducibility is a measure of whether results from a certain experiment can also be obtained by a different team, with other test equipment or in a different lab infrastructure using the same methods [13]. The defined test procedures for determining the GFM inverter parameters should be reproducible at other laboratories with equivalent equipment. Additionally, the test procedures should be valid for a GFM inverter independent of its inner control mechanism.

The project work presented in this paper aims to refine methods for determining the GFM inverter parameters which are easily reproducible and have a high repeatability in their results. The paper is divided into the following sections: Section 2 describes the methodology of the investigations in this paper, Section 3 presents the results and discusses them followed by Section 4 which presents the conclusion and outlook.

## 2. Methodology

For the accurate characterisation of the inertia parameters of a GFM inverter, the relation between frequency stability and inertia is exploited. Two already well established tests, the RoCoF test and the system split test, which are well described in the literature [7], [11], [14] were performed. The GFM inverter used is a prototype with hardware and software developed at Fraunhofer IEE. It consists of a 4-wire power converter hardware using SiC-semiconductors with 70 kHz switching frequency, GFM control based on SelfSync+ (Patent number: DE 102016203123) and is equipped with a graphical user interface (GUI) which can be used as Supervisory Control and to set certain parameters (such as the Ta) in the GFM inverter. It is not possible to set a direct Feedback-Damping in the GUI of the GFM inverter. A bidirectional DC source supplies the GFM inverter and represents a DC bus link emulating the behaviour of a battery storage system, photovoltaic (PV) or inverter interfaced wind turbine generator (WTG). For the RoCoF tests, it is recommended to use a programmable AC grid simulator in order to manipulate the system frequency as necessary.

*2.1 RoCoF tests with grid simulator*

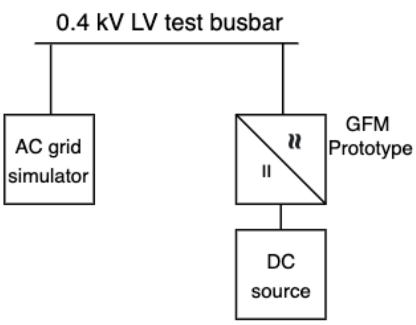


*Fig. 3 Experimental setup for the RoCoF tests*

Fig 3 represents the experimental test setup for the RoCoF tests. The test methodology entails creating pre-defined linear frequency ramps (i.e. constant RoCoF values) with the grid simulator and observing the instantaneous response from the GFM inverter according to its electrical inertia. With respect to reproducibility, these tests have been performed with two different grid simulators. The test methodology, including the utilisation of generic RoCoF values not necessarily reflecting real events, permits determination of characteristic parameters of the tested inverter. The applied RoCoF testing sequences are closely based on the procedure described in prEN 50549-10 [14]. An example of the proposed test sequence is displayed in Fig 4. Starting from an operating point with nominal frequency value of 50 Hz the first constant (positive/negative) RoCoF event is applied for a defined duration until reaching the new frequency operating point f_over/f_under after which the second (negative/positive) RoCoF event is applied until the frequency reaches f_under/f_over. After this a final RoCoF event is applied until the frequency reaches its initial value of 50 Hz again.

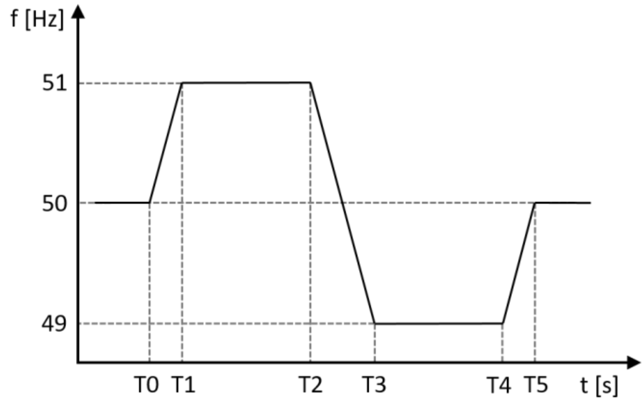


*Fig. 4 RoCoF Test Sequence as per prEN 50549*

The GFM inverter is considered as a black-box and in order to allow for the determination of the Ta (based on a settled / steady state value of the active power), the RoCoF event to be evaluated is the second one, T2 to T3, displayed in Fig 4, started at a frequency value deviating from nominal frequency (i.e. 51 Hz and 49 Hz respectively). This change in frequency of in total 2 Hz combined with a rather low RoCoF value allows sufficient time for the steady state value of the active power to be reached compared to the other two RoCoF events and thus to determine Ta.
In the literature various RoCoF values for determination of the parameters were used however they were not discussed in detail. In Section 3, the presented results will explain which RoCoF values are recommended.

The relation between Ta and the active power contribution is provided in various literature (e.g. [4], [7], [9], and [11]]) and is presented by the Equation 2. As observed through the equation, the RoCoF and the Ta have an inverse relationship. More specifically, the Ta and the generation-demand imbalance (ΔP) during a system disturbance affect the initial RoCoF, however later on the frequency response of DER can be affected additionally by other control approaches like frequency-watt control (P(f) droop) or the frequency containment reserve (FCR).

$$T_a = \frac{f_n}{RoCoF} * \frac{\Delta P}{S_n} \quad (2)$$

*2.2 System split tests*

As a main consequence of a system split event the generator(s) have to supply the entire load in isolated partial grids. Especially large power transits prior to the system split can lead to high load-generation imbalances and strong frequency changes in the split subsystems. Hence such a test enables us to observe the grid-forming behaviour of the inverter in the absence of a supporting grid, similar to the test for the grid-forming capability of internal combustion engines with synchronous machines as in [15]. The experimental test setup is represented in Fig 5.

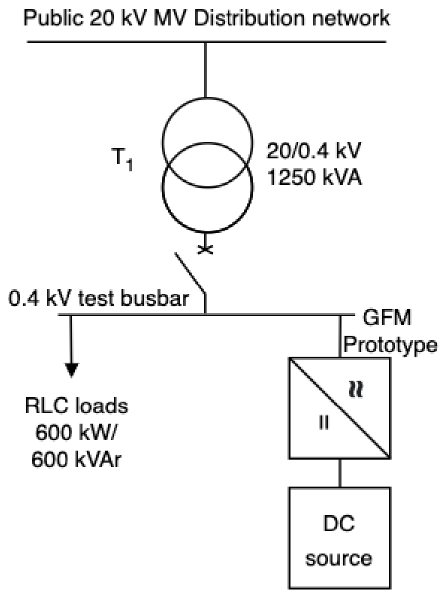


*Fig. 5: Experimental setup for the System split tests conducted at the Fraunhofer IEE SysTec laboratory*

For the system split tests conducted at the Fraunhofer IEE SysTec, the GFM inverter is connected to the medium voltage (MV) grid through a distribution transformer. A programmable RLC load bank is connected in parallel at the low voltage busbar. Before the split is performed, the public network supplies the load, regardless of the operational setpoint of the GFM inverter, whereas after the circuit breaker between the transformer and the low voltage busbar is opened to perform the split, the GFM inverter is expected to independently supply the load. The GFM inverter is provided with an active power setpoint before the system split.

Various test cases are simulated wherein the GFM inverter has an active power setpoint equal to the parallel load, a setpoint lower than the load (surplus load case) and a setpoint greater than the load (surplus generation case).

*2.3 Limitations / Measurement uncertainty*

During the laboratory measurements, certain factors were observed to determine the measurement uncertainty or accuracy. The statistical dispersion of the values assigned to a measured quantity is expressed as measurement uncertainty. [16]. Measurement uncertainty can be divided into Type A where the knowledge of an input value is inferred through repeated measurements and Type B uncertainty where scientific analysis or other information regarding the possible values of the quantity are obtained. The input values for our measurements display a Type B measurement uncertainty distribution [16].

Active power (P) is dependent on voltage (U), current (I) and power factor (cosphi). For amplitudes of U and I we can derive uncertainty from calibration certificates, however regarding the phase angle error of U and I respectively we have to consider data sheet information from the used measurement system and current transducers (in our case Rogowski coils).

The active power expanded measurement uncertainty (EMU) for two selected operating points of the GFM inverter is calculated for the used measurement equipment. The following values are obtained and are presented in Table 2.

Table 2: Expanded Measurement Uncertainty

| | Operating Point A | Operating Point B |
|---|---|---|
| U | 230 V | 230 V |
| I | 5 A | 50 A |
| f | 50 Hz | 50 Hz |
| cosphi | 1 | 1 |
| P | $P_A$ = 3450 W | $P_B$ = 34500 W |
| EMU | EMU_$P_A$ = 2.4 % | EMU_$P_B$ = 0.5 % |

For our frequency (f) measurement an accuracy of +/-1 mHz can be stipulated for the voltage measuring unit following technical data sheets of the used measurement system. This value should be assumed for steady state values of frequency only, but not during transitional periods, particularly encountered during a RoCoF or system split event. This is due to the fact that the used measurement system requires about five voltage cycles (100 ms) for reliable frequency determination. Considering a RoCoF event with 0.1 Hz/s, over a time span of 100 ms frequency changes by 10 mHz. Correspondingly, for a RoCoF event with 2.0 Hz/s, the resulting frequency change would be even 200 mHz. The faster the frequency changes (i.e. the higher the absolute RoCoF value is), the more difficult it becomes to accurately determine the frequency value. Therefore, the measurement interval has to be carefully selected, especially for system split tests where high RoCoF values occur often.

The impact of the measurement uncertainty on the measurement results will be discussed in the next section.

# 3 Results and Discussion

### *3.1 Determination of parameters using RoCoF tests*

The RoCoF tests were performed with the test setup described in Section 2.1 and with the RoCoF values used in [11]. However, the test sequence in [11] was not completely replicable since the damping parameter of the GFM inverter could not be deactivated, but at least the steady state P(f) droop of the GFM inverter was inactive during these tests.
Furthermore, the initially implemented RoCoF of 2 Hz/s which is also the requested RoCoF value for not-disconnection of power generating plants as provided in [17] does not allow for the active power contribution of the GFM inverter to reach a settling point and therefore does not represent the full capability of the instantaneous active power provision.
Therefore, it is prescribed to use lower RoCoF values in conjunction with the methodology described in Section 2.1. This leads to a major improvement in the results as observed in Fig 6 and Fig 7.

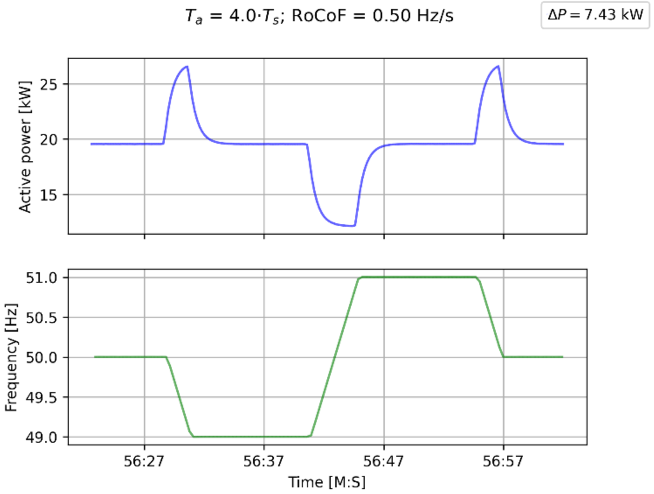


*Fig. 6: Active power output of the GFM* inverter *and system frequency for a RoCoF test sequence with Ta = 4Ts and RoCoF = 0.50 Hz/s*

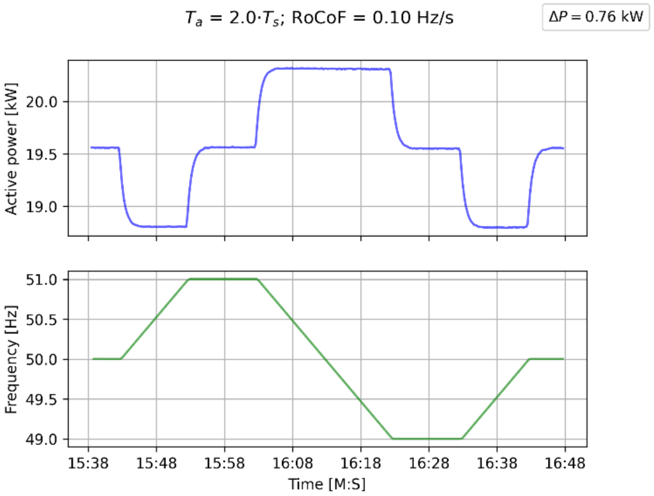


*Fig. 7: Active power output of the GFM* inverter *and system frequency for a RoCoF test sequence with Ta = 2Ts and RoCoF = 0.10 Hz/s*

The tests are conducted with significantly lower RoCoF values between 0.1 and 0.5 Hz/s to observe the effect on the active power contribution ΔP and to calculate the Ta value. The GUI of the GFM inverter is set to three different Ta values (Ts, 2Ts, 4Ts). Here Ts represents a set input for the acceleration time constant in the GUI which is unspecified here in order to maintain the black-box consideration.
For getting correct steady state active power contribution values, it is important to consider all operating limits of the GFM inverter under test (e.g. min. and max. apparent power values).

Table 3 provides an overview of the results for the active power contribution ΔP from the GFM inverter in the different RoCoF tests. For positive RoCoF values (increase of system frequency), the active power output of the GFM - similar to synchronous machines - is decreasing (negative ΔP) and vice versa for negative RoCoF values (decrease of system frequency) the instantaneous active power ΔP is positive.
The magnitude of the instantaneous active power provision for a specific RoCoF value (regardless of whether increasing or decreasing RoCoF) is almost the same and independent of the initial operating setpoint of the GFM inverter. Neglecting measurement and evaluation errors, a linear relationship between the instantaneous active power provision and the acceleration time constant set value Ts is observed, as Ts doubles in value so does the active power provision ΔP Additionally, a linear relationship between the instantaneous active power ΔP and the applied RoCoF values can be observed.

Table 3: Overview of instantaneous active power ΔP for the GFM inverter in the RoCoF tests

| Applied RoCoF [Hz/s] | ΔP [kW] @Ts | ΔP [kW] @2Ts | ΔP [kW] @4Ts |
|---|---|---|---|
| 0.10 | -0.39 | -0.76 | -1.51 |
| 0.20 | -0.77 | -1.50 | -2.99 |
| 0.33 | -1.26 | -2.49 | -4.96 |
| 0.50 | -1.89 | -3.72 | -7.41 |
| -0.10 | 0.39 | 0.76 | 1.51 |
| -0.20 | 0.77 | 1.51 | 3.00 |
| -0.33 | 1.26 | 2.50 | 4.97 |
| -0.50 | 1.89 | 3.73 | 7.43 |

Based on equation No. 2, the results from Table 3 and the two reference parameters (fn = 50Hz, Sn = 43.5 kVA) it is possible to determine the acceleration time constants Ta of the GFM inverter for the three different Ts set values. Table 4 gives an overview of the results.

Table 4: Overview of determined acceleration time constant Ta for the GFM inverter based on the RoCoF tests

| Applied RoCoF [Hz/s] | Ta1 [s] Ts | Ta2 [s] 2Ts | Ta4 [s] 4Ts |
|---|---|---|---|
| 0.10 | 4.33 | 8.44 | 16.78 |
| 0.20 | 4.28 | 8.33 | 16.61 |
| 0.33 | 4.24 | 8.38 | 16.70 |
| 0.50 | 4.20 | 8.27 | 16.47 |
| -0.10 | 4.33 | 8.44 | 16.78 |
| -0.20 | 4.28 | 8.39 | 16.67 |
| -0.33 | 4.24 | 8.42 | 16.73 |
| -0.50 | 4.20 | 8.29 | 16.51 |

Assuming the black-box consideration and treating the input Ta values as unknown, it is possible to calculate at least mean values and the standard deviations. These are presented in Table 5.

Table 5: Overview of determined acceleration time constant Ta for the GFM inverter based on the RoCoF tests

| Statistical calculation | Ta1 [s] Ts | Ta2 [s] 2Ts | Ta4 [s] 4Ts |
|---|---|---|---|
| Mean value | 4.26 | 8.37 | 16.66 |
| Standard deviation | 0.05 | 0.06 | 0.11 |

The mean values show a good linearity, and the standard deviations are in the range of 1% or even smaller. Herewith one can state, that the performed RoCoF tests are particularly suitable for determination of the GFM inverter acceleration time constant Ta parameter.

Following Section 2.3 applying lower RoCoF values also allows for a more accurate frequency and thus also RoCoF value measurement, by a more reliable determination of the RoCoF event, i.e. knowing start and end time of the event as well as the value of the frequency change.

### *3.2 Determination of parameters using system split tests*

As stated in Section 2.2, system split tests are useful for determination of accuracy, dynamic and robustness of the GFM inverter under test in islanded operation.

Following, selected results from various system split tests for assessment of the steady state accuracy of the frequency dependent active power generation from the GFM inverter will be presented in this paragraph. These tests are conducted with activated P(f) and Q(U) droops. The P(f) droop is of special importance due to the fact, that in the electrical grid nearly all DER units and plants are equipped with a similar function which is well known as Limited Frequency Sensitive Mode (LFSM).

In the two following presented scenarios, in Fig 8 and Fig 9, the reaction of the GFM inverter after the system split is studied and analysed.

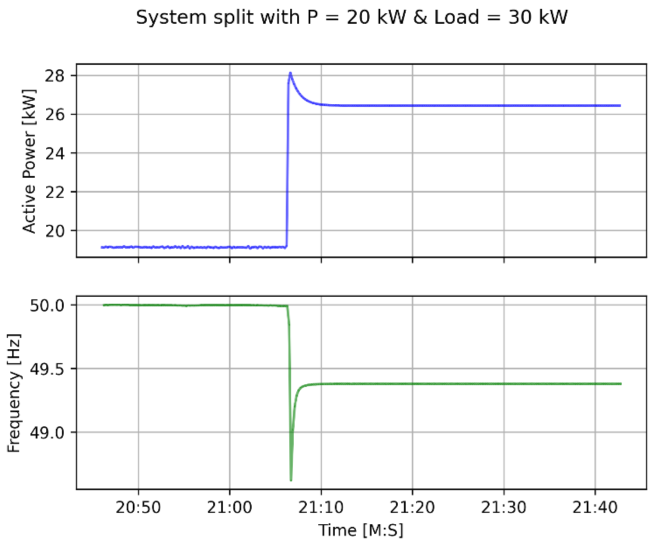


*Fig. 8: System frequency and active power generation of the GFM inverter for a System split test with GFM inverter output of 20 kW and ohmic load of 30 kW prior to the system split.*

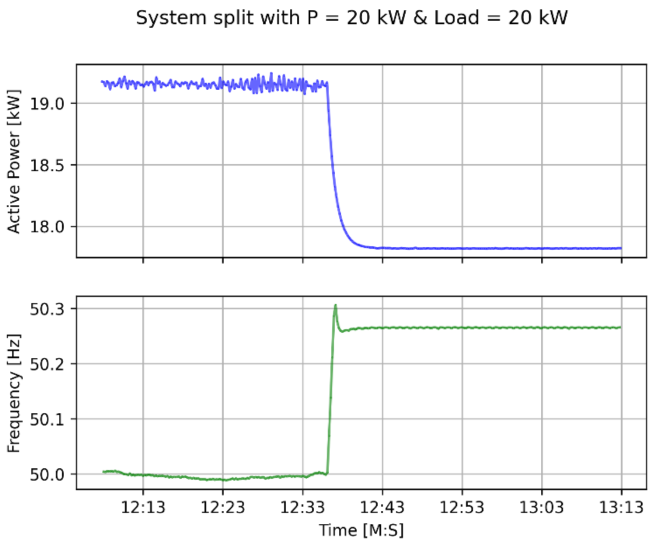


*Fig. 9: System frequency and active power generation of the GFM inverter for a System split test with GFM inverter output of 20 kW and ohmic load of 20 kW prior to the system split.*

Although in both tests, depicted in Fig 8 and Fig 9, the GFM inverter setpoint prior to the system split is 20 kW, the active power of the GFM inverter has a different behaviour in each scenario due to the differing ohmic load setpoints of 30 kW and 20 kW respectively. The deviation of the GFM prototype active power generation from its setpoint (20 kW) prior to the system split (in both scenarios in Fig 8 and Fig 9) may be caused by several reasons such as not optimised control settings especially under imbalanced voltages (at public grids), tolerances of the built-in electronic components and uncertainties of the used measurement equipment.

When the GFM active power setpoint prior to the system split is equal to the load setpoint, the RoCoF of the system frequency is slower as compared to the RoCoF for the case with higher setpoint imbalance before the system split. Additionally, the steady state system frequency has a noticeable deviation when the GFM setpoint and the ohmic load setpoint are unequal (Fig 8) in comparison to the scenario where they are equal (Fig 9).

In terms of determination of the GFM inverter characteristic parameters, the conducted system split test sequences proved unfavourable for calculating the damping D since the loads used were voltage dependent. This meant that the load power setting could fluctuate depending on the voltage. This could also be avoided by deactivating the Q(U) droop characteristic of the GFM inverter. These recommendations should be considered for the implementation of the system split test for the GFM inverter characteristic determination.

If the GFM inverter increases its active power output after system split, then the system frequency (transient and steady state) is decreasing (Fig 8) and vice versa for a negative load jump the system frequency is increasing (Fig 9).

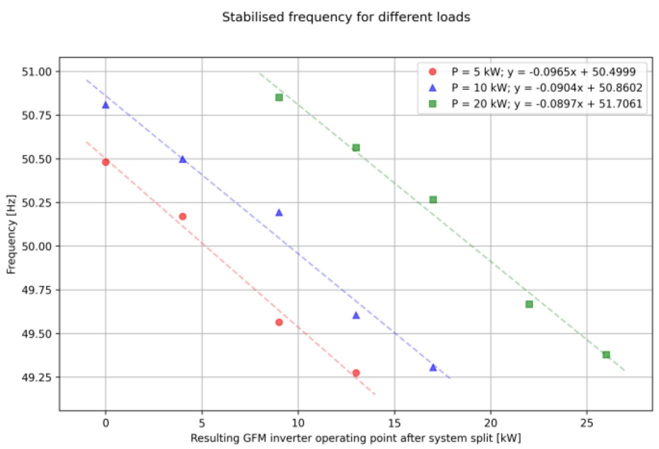


*Fig. 10: Overview of the resulting GFM inverter steady state active power vs. system frequency values for the system split tests and three different active power setpoints prior to the system split.*

The steady state active power values of the GFM inverter for system split tests with various combinations of GFM inverter and ohmic load settings are presented in Fig 10. Based on these results it is possible to determine the P(f) droops for the 5 kW, 10 kW and 20 kW GFM inverter active power setpoint at nominal frequency of 50 Hz. It can be clearly seen, that the droop values of the three active power setpoints are remarkably comparable, indicating that the GFM control works very well, regardless of the GFM inverter active power generation prior to the system split.

## 4 Conclusions and Outlook

The paper presents two tests for determining characteristic parameters of GFM inverters. An emphasis is set on the repeatability and the reproducibility of the tests. Out of the conducted tests and the analysed results, the RoCoF test as well as the system split tests showed good repeatability and reproducibility. Based on the conducted tests, it can be remarked that it is important to note that the test setup and the experimental conditions present during the test should be recorded in detail and followed precisely in order to obtain a reproducible result. This can be concluded since the RoCoF tests presented in this paper considered a deactivated P(f) droop in order to observe the inertia related active power contribution. In order to reproduce these results at another laboratory, the same pre-conditions and parameters would have to be considered.

With respect to measurement uncertainty, it can be concluded that the used measurement equipment, especially the voltage and current sensors and its measurement ranges should be selected according to type, rated power and setpoint of GFM inverter under test. For measurement of instantaneous active power provision and for determination of inertia constant Ta the accuracy (magnitude and phase error) of the current sensors is of special importance.

Furthermore, it can be stated, that the acceleration time constant Ta can be determined well by means of RoCoF tests, unless operational limitations of the GFM inverter under test are exceeded. For achieving steady state active power contributions, the duration of the RoCoF event should be selected adequately. Good reproducibility using different grid simulators, as well as with different RoCoF settings and different operational setpoints has been detected.

Finally, we were able to further develop existing testing procedures for GFM inverters. It can also be stated that for the refined / proposed GFM inverter testing procedures, in general already existing laboratory infrastructures and equipment used for testing of generating units with grid following converters could be utilised as well.

Further work on this topic will be conducted through other projects and working committees in order to ensure the grid supply stability.

## 5 Acknowledgements

We acknowledge the support of our work by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Project Management Juelich (PTJ) within the project “Netzregelung 2.0” (FKZ 0350023A) and the support by the German Federal Ministry of Education and Research (BMBF) within the project “RESIST” (FKZ 03SF0637). Only the authors are responsible for the content of this publication. This publication does not reflect the consolidated opinion of the project consortia.

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# Towards Standardised Testing Procedures for Inertia Provision of Grid Forming Inverters

Nils Schäfer, Siddhi Shrikant Kulkarni, Gunter Arnold, Vivek Vinod Balani Mahtani

21st Wind & Solar Integration Workshop, 12 – 14 October 2022

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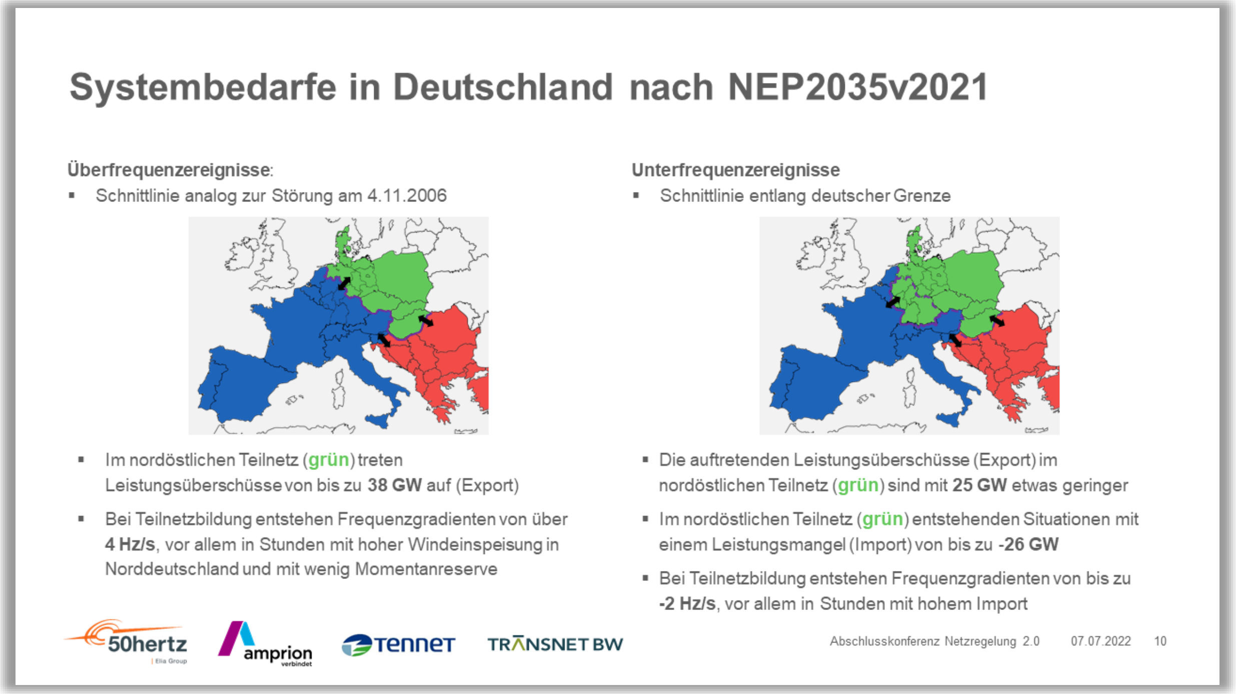
# Motivation

- Design case discussed by German TSOs:
  - System Split scenarios for synchronous area of Continental Europe
- Power imbalances & resulting high RoCoF values feared like in former events, e.g. 2006-11 and 2021-01
- German TSOs see the need for Grid Forming Inverters to be installed down to the LV level.

For us this means, in the future type testing of Grid Forming Inverters will be needed.




Source: Hennig, T.: “Zukünftige Systembedarfe an Momentanreserve und Anforderungen an netzbildende Umrichter”, end of project conference Netzregelung 2.0, July 2022

RoCoF = Rate of Change of Frequency

# Contents





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# Introduction

## R&D project “Netzregelung 2.0”

- German R&D Project dealing with the subject „Grid control“ (“Netzregelung 2.0” (fraunhofer.de))

- The aim of the project was to prove that the interconnected electrical system – and, in the event of a fault, also electrically separated parts of it – can be operated in a stable manner even with very high converter shares using suitable control methods
  - Grid Forming (GFM) Inverter control is an R&D focus of this project
  - Component and field / system tests with the developed GFM inverter control

- Duration: Dec. 2017 – Aug. 2022
- Project consortium: Fraunhofer IEE, Technische Universität Braunschweig, Universität Kassel, SMA Solar Technology AG, Forum Netztechnik und Netzbetrieb im VDE – VDE|FNN, DERlab e.V., Deutsche Energieagentur dena, Amprion GmbH, TenneT TSO GmbH, 50Hertz Transmission GmbH, TransnetBW GmbH, EWE NETZ GmbH, innogy SE, Mitteldeutsche Netzgesellschaft Strom mbH (MITNETZ STROM), Westnetz GmbH, Siemens AG



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# Introduction

*Which tests are necessary for Grid Forming Inverter(s), in order to show compliance with predefined requirements (e.g. in grid codes)?*

## Behaviour of Grid Forming Inverter(s)

### Grid Forming / Voltage Source
- V setpoint accuracy & dynamics
- f setpoint accuracy & dynamics
- Robustness
- Int. Impedance

### Electrical Inertia Provision
- Accuracy & dynamic of ΔP
- Inertia H / Acceleration time Ta
- Damping D

### Overload & Fault Ride Through (FRT) capabilities
- Overload current limit
- FRT successful (y/n)?
- Fault current contribution
- Fault voltage-support

### Power Quality (esp. Harmonics)
- Voltage & current harmonic emission
- Voltage & current unsymmetries

### Active & Reactive Power control
- P setpoint accuracy & dynamics
- LFSM-O / -U
- Q setpoint accuracy & dynamics
- Q(V), etc.

### Anti-Islanding Detection
- Disconnection time
- Non-detection zone(s)

# Introduction

*Which tests are necessary for Grid Forming Inverter(s), in order to show compliance with predefined requirements (e.g. in grid codes)?*

**Behaviour of Grid Forming Inverter(s)**

**Grid Forming / Voltage Source**
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**Electrical Inertia Provision**
- Accuracy & dynamic of $\Delta P$
- Inertia H / Acceleration time Ta
- Damping D

**Overload & Fault Ride Through**
- support

**Power Quality**
- unsymmetries

**Active & Reactive**
- dynamics
- Q(V), etc.

**Anti-Islanding Detection**
- Disconnection time
- Non-detection zone(s)

Our specific goals were the further development of laboratory tests for the validation of GFM characteristic parameters (Inertia and Damping).

Tests should be independent of the GFM control (Black-box consideration) and allow for repeatability and reproducibility.

$Ta = 2*H$

# Introduction

## Grid Forming (GFM) Inverter prototype

### Rapid Inverter Control Prototyping Solution

RICOSO

| Technical data power amplifier | | |
|---|---|---|
| Power Range @ 400V | 43.5 kVA | Scalable to 215 kVA (t.b.v.) |
| AC Voltage ($V_{LL}$) | 340 V – 620 V | |
| AC Current | 63 A | |
| Output frequency | ~ 2.5 kHz | High dynamics (t.b.v.) |
| Unbalanced load capable | 100 % | 4-phase |
| Dimensions | 6 RU / 19“ | |
| Topology | 3-Level ANPC SiC-Mosfets @ 72 kHz | |



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# Introduction

## Grid Forming (GFM) Inverter prototype application

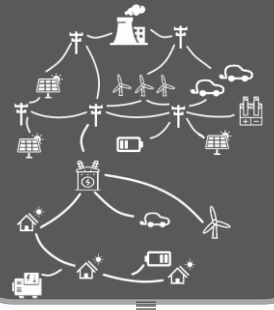
### Rapid Inverter Control Prototyping Solution

**Fast implementation and further development of control algorithms for power converters in real-world applications**

GUI of the GFM inverter prototype used to set various parameters such as:

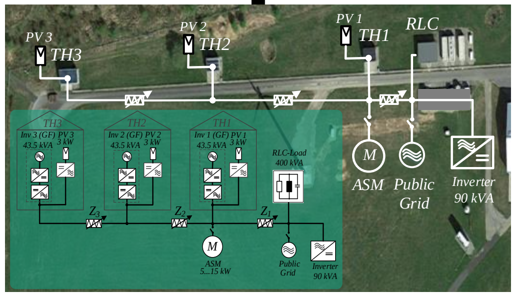
- Ta
- P(f) droop
- Q(V) droop
- and many others…

Grid Environment

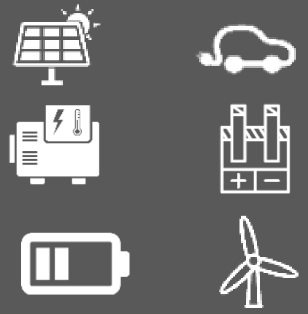


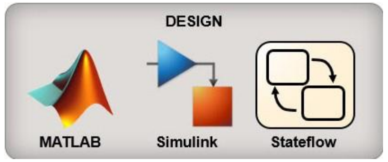
Real time computer

RICOSO




Custom Control Prototyping






Model Based Toolchain

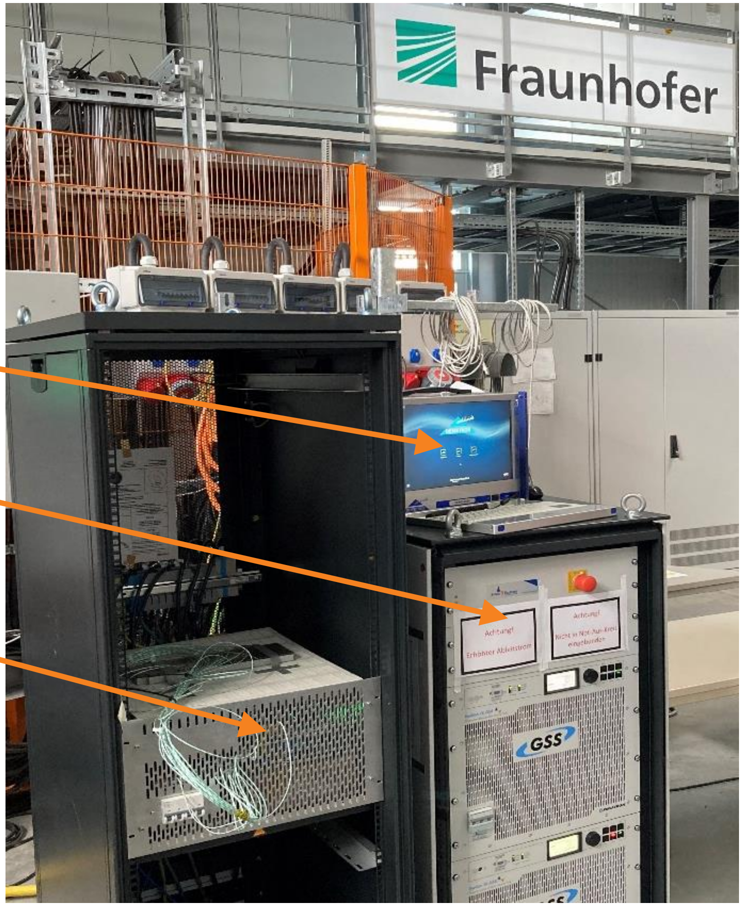
# Contents

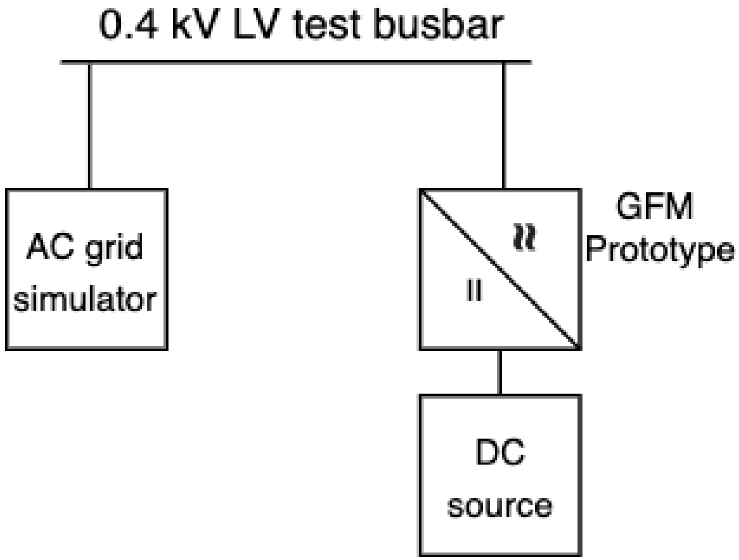
# Provision of electrical inertia

## Experimental setup

**Experimental setup in the IEE test centre “SysTec” (used in a similar way for a long time in the context of grid connection tests, e.g. according to FGW TG3).**

- Powerful measurement data acquisition system
- Bidirectional DC source (40 kVA) for supplying the EUT (equipment under test)
- EUT: GFM inverter prototype (43.5 kVA) with hardware and software developed at Fraunhofer IEE
- Programmable AC grid simulator (90 kVA & 1 MVA) suitable for pos. & neg. f-ramps




Schematic of the experimental setup

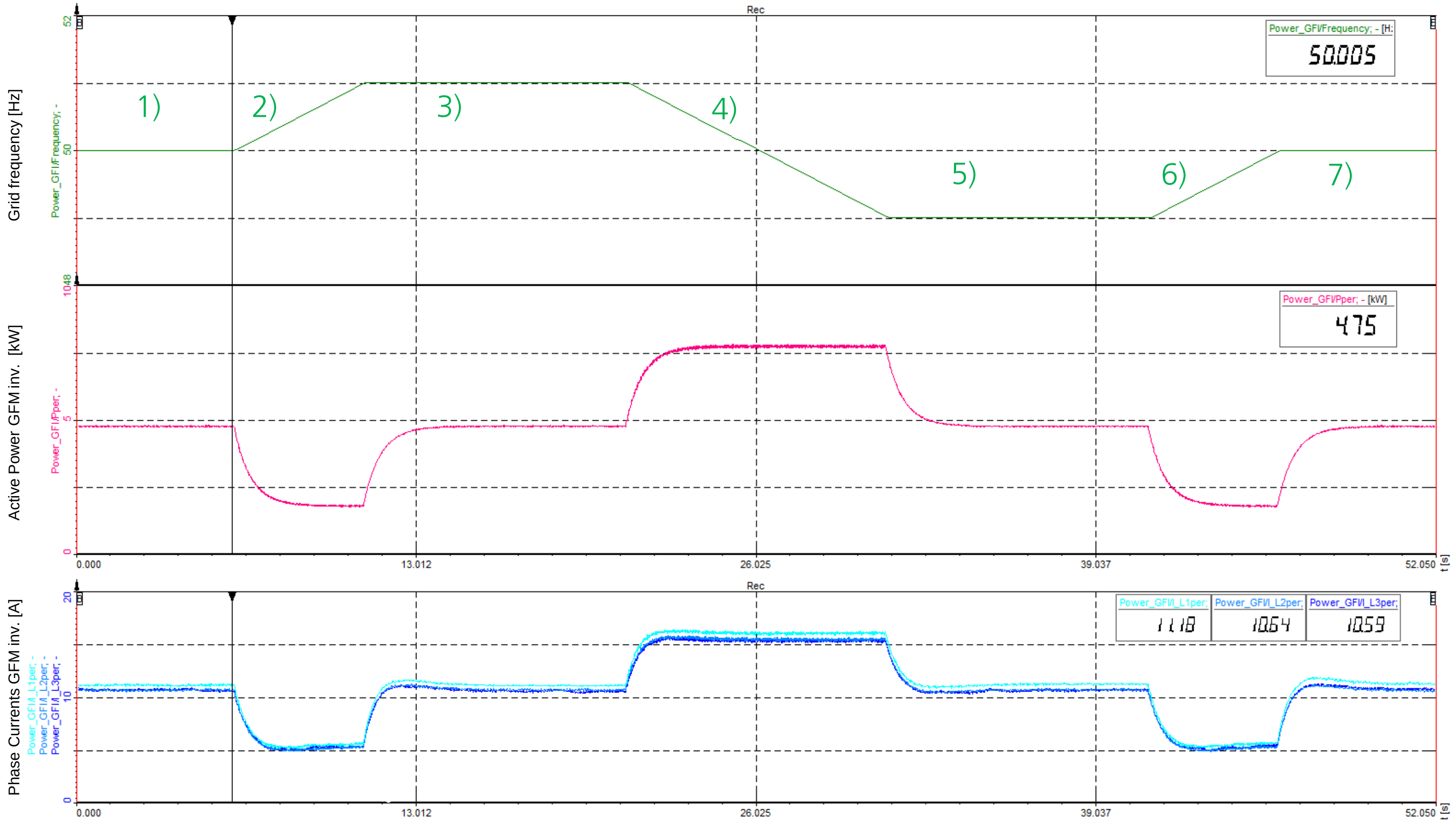
# Provision of electrical inertia

## RoCoF (Rate of Change of Frequency) test with grid simulator

- Exemplary RoCoF test sequence (according to prEN 50549-10)
- Generic test sequence with linear frequency ramps (i.e. constant RoCoF values) created with an AC grid simulator
- A set value for the acceleration time constant is entered into the GUI. Considered as unknown for the black-box consideration.

**Steps of the exemplary test sequence:**

1) Start: 50 Hz const.
2) +0.2 Hz/s RoCoF: 50 Hz → 51 Hz
3) 51 Hz const. for approx. 10 s
4) -0.2 Hz/s RoCoF: 51 Hz → 49 Hz
5) 49 Hz const. for approx. 10 s
6) +0.2 Hz/s RoCoF: 49 Hz → 50 Hz
7) 50 Hz const.




RoCoF test with grid simulator for a grid forming (GFM) inverter (rated power 43.5 kVA)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# Provision of electrical inertia

## Results of the RoCoF tests

| ΔP [kW] ROCOF [Hz/s] | P[kW] Ts | P[kW] @2Ts | P[kW] @4Ts |
|---|---|---|---|
| 0.10 | -0.39 | -0.76 | -1.51 |
| 0.20 | -0.77 | -1.50 | -2.99 |
| 0.33 | -1.26 | -2.49 | -4.96 |
| 0.50 | -1.89 | -3.72 | -7.41 |
| -0.10 | 0.39 | 0.76 | 1.51 |
| -0.20 | 0.77 | 1.51 | 3.00 |
| -0.33 | 1.26 | 2.50 | 4.97 |
| -0.50 | 1.89 | 3.73 | 7.43 |

### Steady-state change of active power ΔP

- Active power curves show a PT1 behaviour
- Active power change proportional to the acceleration time constant set value Ts
- Active power change also proportional to RoCoF ramp

| Ta_calc [s] ROCOF [Hz/s] | Ta1 [s] Ts | Ta2 [s] 2Ts | Ta4 [s] 4Ts |
|---|---|---|---|
| 0.10 | 4.33 | 8.44 | 16.78 |
| 0.20 | 4.28 | 8.33 | 16.61 |
| 0.33 | 4.24 | 8.38 | 16.70 |
| 0.50 | 4.20 | 8.27 | 16.47 |
| -0.10 | 4.33 | 8.44 | 16.78 |
| -0.20 | 4.28 | 8.39 | 16.67 |
| -0.33 | 4.24 | 8.42 | 16.73 |
| -0.50 | 4.20 | 8.29 | 16.51 |

### Calculated acceleration time constant Ta_calc

- Almost proportional to the setting value Ts and conditionally independent of the ROCOF ramp
- Applied equation: $$T_a = \frac{f_n}{RoCoF} * \frac{\Delta P}{S_n}$$
- with the values: $f_n$ = 50 Hz, $S_n$ = 43.5 kVA



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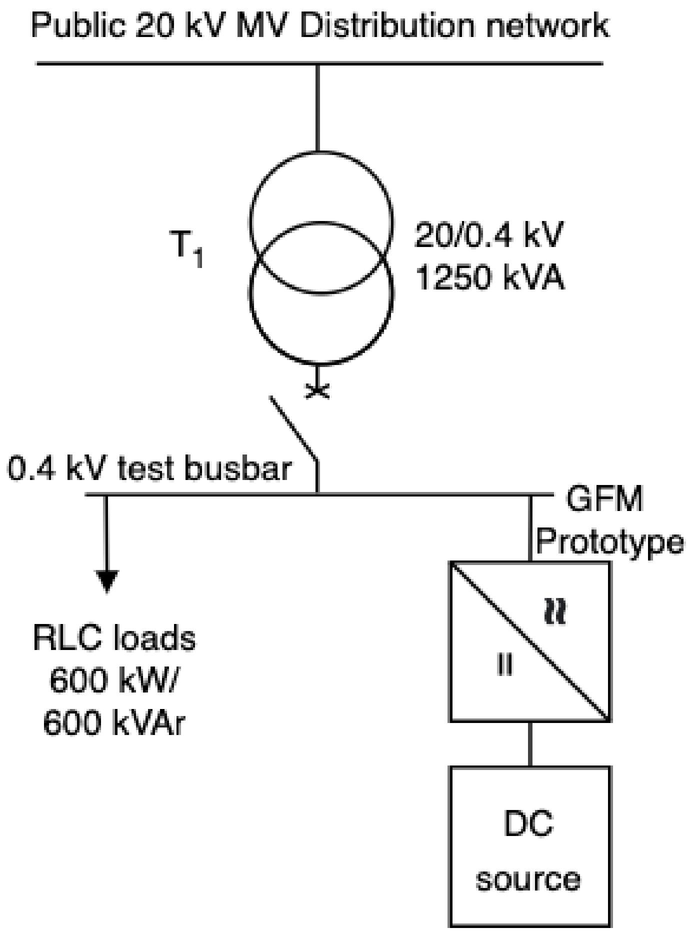
# Behaviour during system split

## Experimental setup

- Dynamic transition:
  Interconnected operation → Islanded operation

- Different properties can be investigated (depending on parameterisation)
  - Grid-forming capability:
    Stable behaviour during dynamic load changes; f droop, V droop
  - Unintended islanding:
    Anti islanding detection (AID) functioning, disconnection times and non-detection conditions

- Experimental setup:
  - EUT (equipment under test): GFM inverter with DC source
  - Configurable RLC load bank (resonant circuit with defined quality factor)
  - Circuit breaker for separation / disconnection from interconnected system




Schematic of the experimental setup

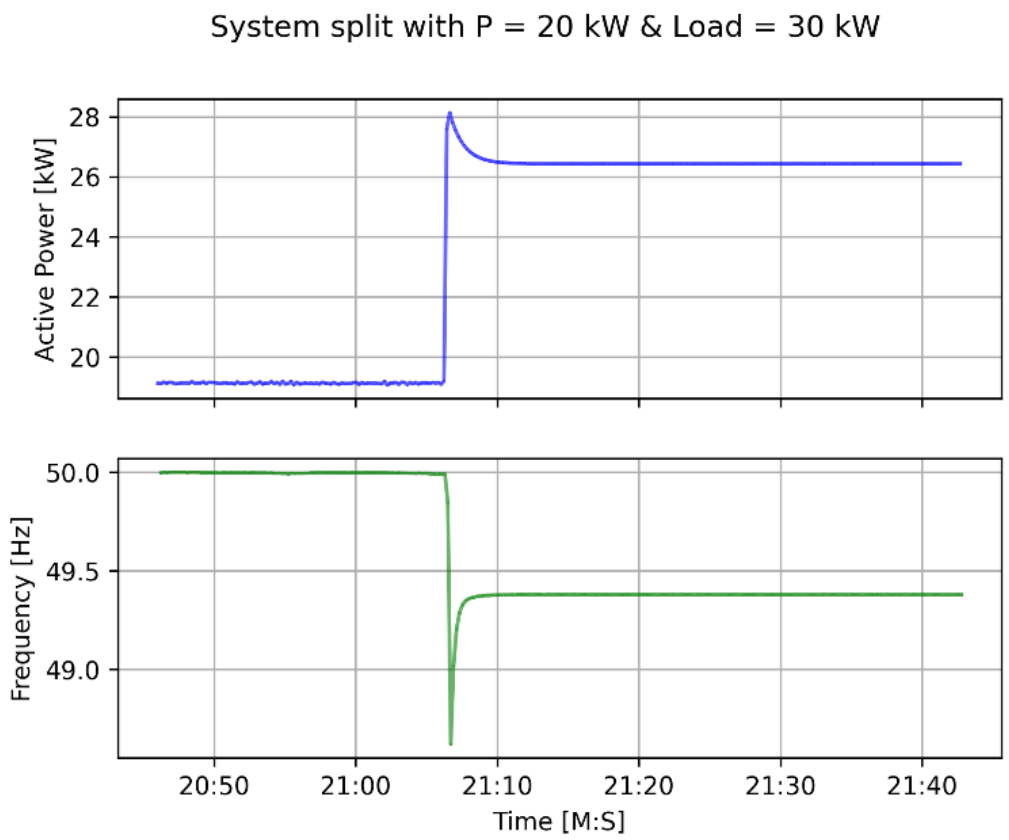
# Behaviour during system split

## System split test with load bank

- Exemplary system split test sequence (according to IEC 62116) with abrupt change from interconnected to islanded operation

1) Start: P_GFI = 19.2 kW,
   P_RLC = 29.7 kW,
   f_grid = 50.0 Hz,
   V_grid = 232 V
2) Separation from interconnected system
3) GFM inverter „takes over“ the load; transient drop of frequency with a RoCoF of 6-8 Hz/s to a minimum value of 48.6 Hz
4) Stabilisation by intervention of the GFM inverter control (droops):
   P_GFI = 26.4 kW,
   P_RLC = 26.2 kW,
   f_grid = 49.39 Hz,
   V_grid = 219 V

Frequency dynamic is too fast to analyse the system split event




System split test for a GFM inverter (rated power 43.5 kVA)

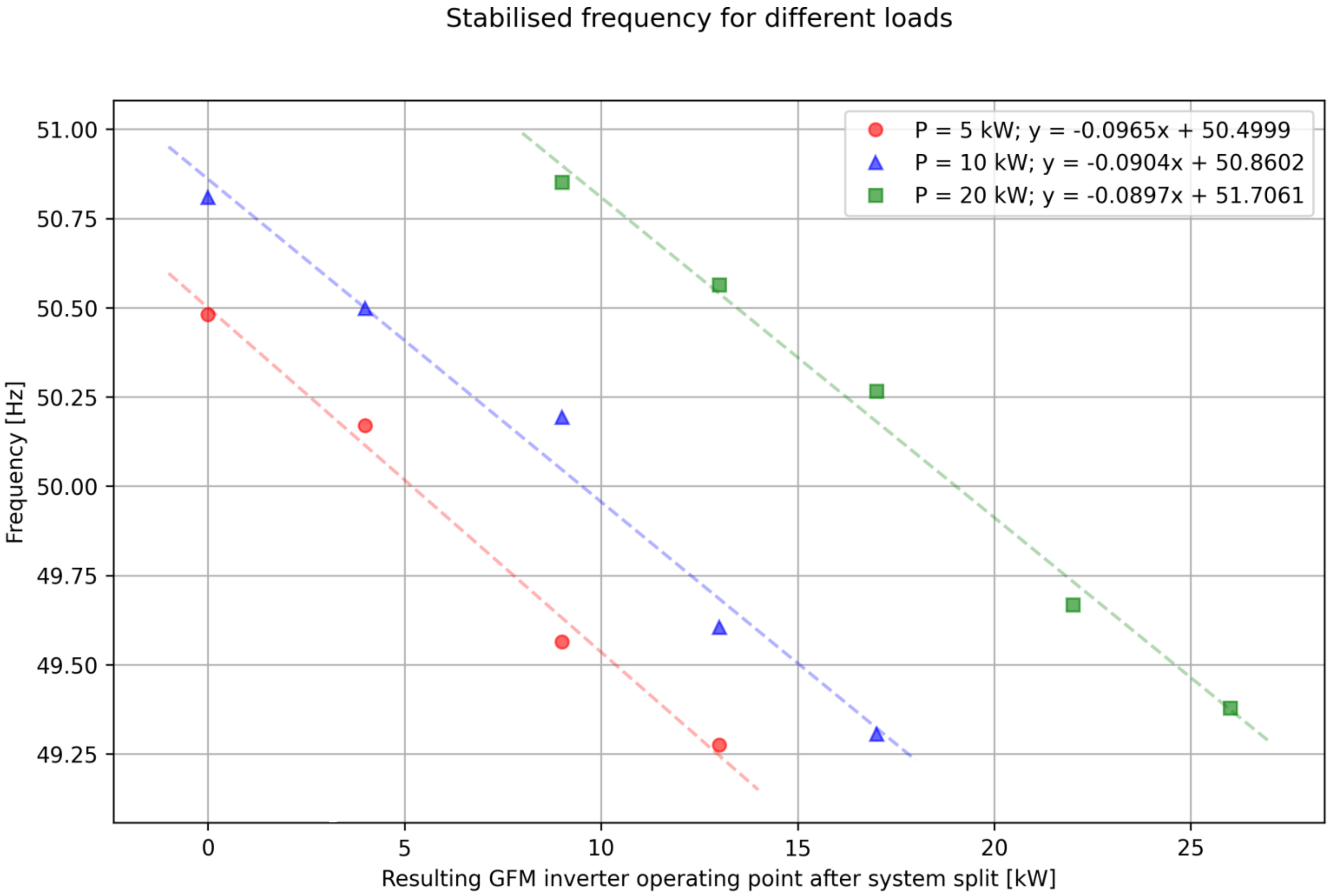
# Behaviour during system split

## Results of the system split tests

- System split tests (test sequence according to IEC 62116) with abrupt change from interconnected to islanded operation

- Parameterisation of GFM inverter control:
  - Anti islanding detection (AID) inactive
  - P-f-droop active
  - Q(V) active

- The reproducibility in the droop slopes (~ -0,09 Hz/kW) reinforces our confidence in the applicability of GFM technology.




System split test with load bank for a grid forming (GFM) inverter (rated power 43.5 kVA)



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# Contents

# Conclusions and Outlook

## Achieved Milestones

- Further developed tests for validation of GFM inverter characteristic parameters.
- Investigated test methods can be performed with laboratory infrastructures and test facilities existing from tests with grid following / grid supporting inverters.
- Blackbox consideration still produced remarkable repeatability and reproducibility through both RoCoF and System Split tests.
- Due to the high frequency dynamic in the System Split tests, the RoCoF tests are preferred for validating the Ta.

## Future Work

- Damping parameter assessment needs voltage independent loads in order to capture the damping effect.
- Continue study of GFM inverters through various other projects.
- Emphasis should be laid on measurement uncertainty and errors introduced through the test environment.

Robustness in the testing procedures for the parameter validation should be aimed at!

# Thank you for your attention!

# Contact

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Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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Federal Ministry of Education and Research

We acknowledge the support of our work by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Project Management Juelich (PTJ) within the project "Netzregelung 2.0" (FKZ 0350023A) and the support by the German Federal Ministry of Education and Research (BMBF) within the project "RESIST" (FKZ 03SF0637). Only the authors are responsible for the content of this publication. This publication does not reflect the consolidated opinion of the project consortia.