Test Case 14

Author Luigi Pellegrino (RSE), Riccardo Lazzari (RSE), Salvador Ceballos (TEC), Rodríguez Emilio (TEC), Efren Guillo Sansano (UST), Ha Nguyen (DTU)

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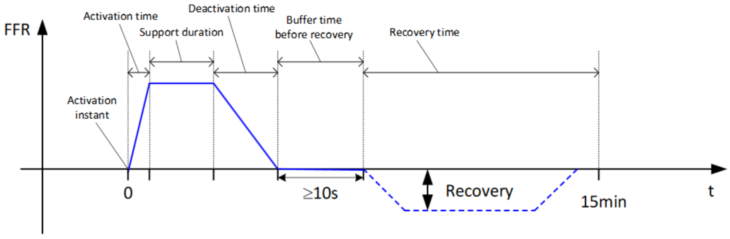
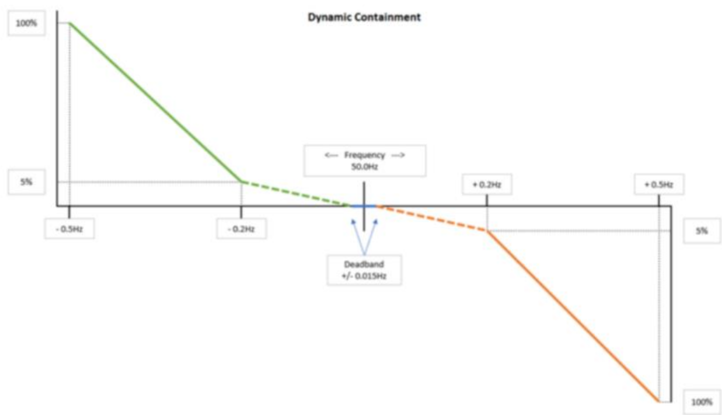
Name of the Test Case	Synthetic inertia and fast frequency response/control provided by converter-based resources
Narrative	The increasing penetration of DERs is reducing the inertia of existing power systems. However, power converters can provide services such as FFR and SI, in order to limit the frequency deviations. An assessment of the frequency dynamics requires multiple experiments to take into account the interaction between the traditional components and the converters as well as the specifications provided by different TSOs.
Function(s) under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	The FuIs are implemented in each converter controller. In this TC, several FuIs are investigated: *Fast frequency response* and *Synthetic Inertia* provided by converters, considering the specification of different countries. **Fast Frequency Response**  ***ENTSO-E specification[1]:*** *Main requirements:* Activation threshold frequency and maximum full activation time (3 configurable values): • 49.7 Hz, 1.3 s • 49.6 Hz, 1 s • 49.5 Hz, 0.7 s Minimum support duration = 5 s Maximum power overshoot = 0.35*P_{pre} (being P_{pre} the prequalified FFR capacity) Deactivation rate = 0.2*P_{pre}/s (measured as the average rate over an integration window of one second) and with no power step higher than 0.2*P_{pre} Buffer + recovery time = 900 s Recovery maximum power = 0.25* P_{pre} Dead-band = +/-50 mHz

[1] https://www.svk.se/siteassets/aktorsportalen/tekniska-riktlinjer/ovriga-instruktioner/technical-requirements-for-fast-frequency-reserve-provision-in-the-nordic-synchronous-area-1.pdf

Italian specification:
Activation instant <= 300 ms
Activation time <= 1 s
Support duration = 30 s
Deactivation time = 300 s
Buffer time + Recovery time = 200 s
FFR Maximum Power = 5 ÷ 25 MW
Recovery Maximum Power = 2 MW (or more if the frequency is within the dead-band)
Dead-band = +/- 50 mHz
ΔP/Δf = tbd

UK specification:
Dead-band: +/- 15 mHz
Small linear delivery: between 15 mHz and 200 mHz (maximum of 5% at 200 mHz)
Knee point activation: +/- 200 mHz
Full delivery: +/- 500 mHz is 100%
Linear delivery knee point: 200 mHz
Activation time <=1s (but no faster than 0.5 s)



Synthetic inertia

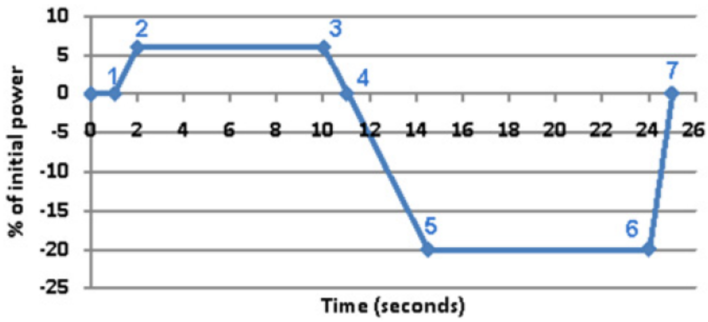
Hydro-Québec Transmission system[2]:
Inertial response requirements:

- Activated at a given frequency threshold (frequency deviation)
- An adjustable dead band from -0.1 Hz to -1.0 Hz (with respect to nominal frequency)
- Rise time (1-2): ≤ 1.5 s
- Maximum power overproduction (2-3): at least 6% of rated power
- Max. overproduction duration (1-4): at least 9s
- Transition time (3-5): ≥ 3.5 s

[2] http://www.hydroquebec.com/transenergie/fr/commerce/pdf/2_Requirements_generating_stations_D-2018-145_2018-11-15.pdf

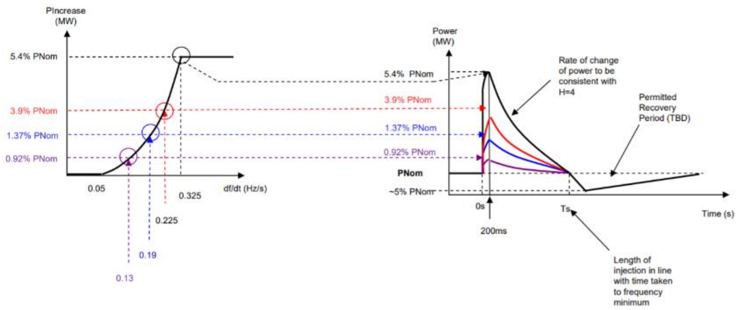
<table>
<tr><td></td><td>

- Max. power decrease during recovery (5-6): 20% of rated power
- Be able to operate repeatedly with a 2 min delay after the end of the recovery period following the previous operation
- *Recovery time: not defined yet*



Nationalgrid-UK (proposal)[3]:

- Activated scheme: ROCOF (df/dt)
- Max. power overproduction: 5.4% of rated power for a ROCOF ≥ 0.325 Hz/s.
- Rise time: 200 ms
- Max. power decrease during recovery: 5% of rated power
- *Max. overproduction duration: not defined yet*
- *Recovery time: not defined yet*
- *Transition time: not defined yet*



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<tr><td>Object under Investigation (OuI)
"the component(s) (1..n) that are to be qualified by the test"</td><td>Set of converters controllers on which the FFR and SI are implemented.</td></tr>
<tr><td>Domain under Investigation (DuI)
“the relevant domains or sub-domains of test parameters and connectivity.”</td><td>Electrical domain.
ICT domain (in case of remote control by system operator for changing function parameters).</td></tr>
<tr><td>Purpose of Investigation (PoI)
The test purpose in terms of Characterization, Verification, or Validation</td><td>PoI 1: Verification of the behavior of providing FFR and SI for different devices (PV, Wind, ESS, etc).</td></tr>
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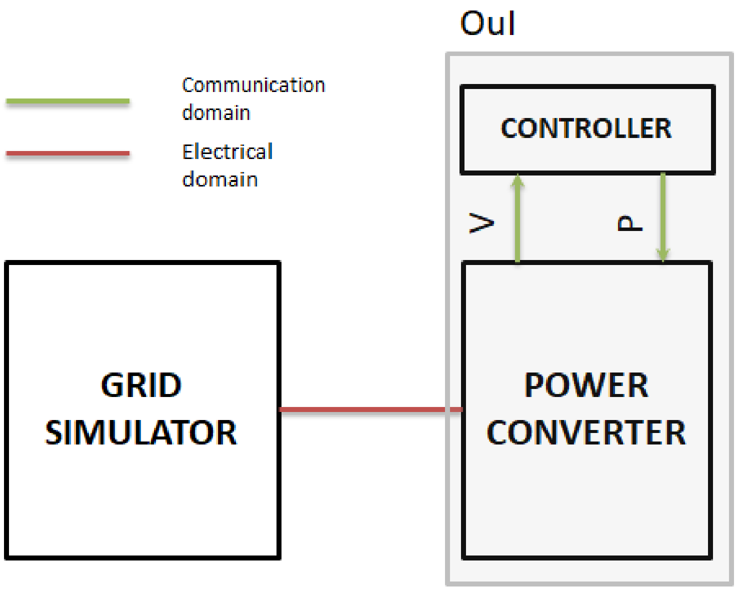
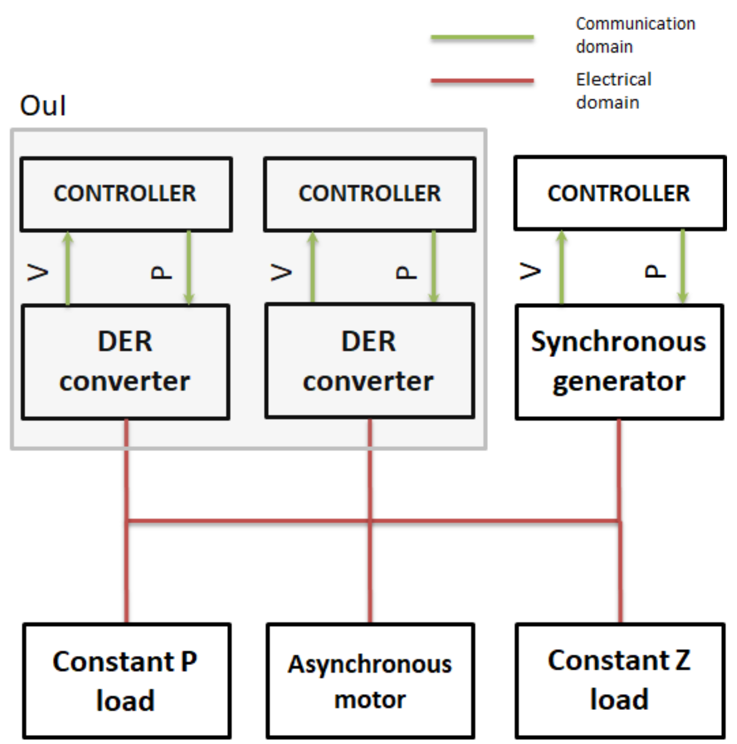
[3] https://www.nationalgrideso.com/document/10331/download

	PoI 2: Validate that FFR and SI limit the Rate Of Change Of Frequency (ROCOF) and the frequency deviations considering different specification and also the interaction among power converters and synchronous machine.
System under Test (*SuT*) Systems, subsystems, components included in the test case or test setup.	For PoI 1: Grid simulator which sets the frequency connected to a power converter with the OuI.  For PoI 1, PoI 2: In order to get insights from the test results, a simple benchmark is selected. The SuT (see figure below) is composed of: • 3 synchronous generators that will be increasingly replaced by power converters. • 3 loads (considering asynchronous machines, constant power loads, constant impedance loads, etc.).

	
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT.	Other frequency control such as Frequency Containment Reserve (FCR). Other high-level controllers (i.e., active and reactive power control).
Test criteria (*TCR*) Formulation of criteria for each PoI based on properties of SuT; encompasses properties of test signals and output measures.	For PoI 1: Comparison between the FFR and SI specification requirements (listed in *Function(s) under Investigation* field) and the experiment results. The test answers to the following question: Is the power converter compliant with the FFR specification? Is the power converter compliant with the SI specification? For PoI 2: Evaluation of the ROCOF and the frequency deviation considering different system configuration in terms of DERs penetration. The test answers to the following questions: Is the system stable under the different configurations? Is the frequency and ROCOF maintained within the limits? Is there any interaction between the devices providing grid services?
Target Metrics *(TM)* Measures required to quantify each identified test criteria	For PoI 1: see *Function(s) under Investigation* field. For PoI 2: At power system level: Frequency variation (ROCOF, Frequency nadir, Steady State frequency, time recovery).

		At component level: Speed of response, Settling time, Power Overshoot, support duration, max power undershoot during recovery
	Variability Attributes *(VA)* controllable or uncontrollable factors and the required variability; ref. to PoI.	For PoI 1: Frequency variation, power set-point, voltage and current harmonics, measures accuracy. For PoI 2: Mechanical Inertia, Non-controllable DER production and load consumption, grid parameters, communication and controller delay, interaction between each power converter providing FFR and SI and other components.
	Quality Attributes *(QA)* threshold levels for test result quality as well as pass/fail criteria.	For PoI 1: *Pass/fail criteria:* • All the specification listed in the FuI field. • System fail (one or more components disconnected) *Quality attributes:* • Sampling time: 100 µs • Resolution: frequency 0.01 Hz, voltage 0.001 pu and current 0.01 pu • Measurement point: one for each resource For PoI 2: *Pass/fail criteria:* • Frequency nadir: 48 Hz • System fail (one or more components disconnected) *Quality attributes:* • Sampling time: 100 µs • Resolution: frequency 0.01 Hz, voltage 0.001 pu and current 0.01 pu • Measurement point: one for each resource

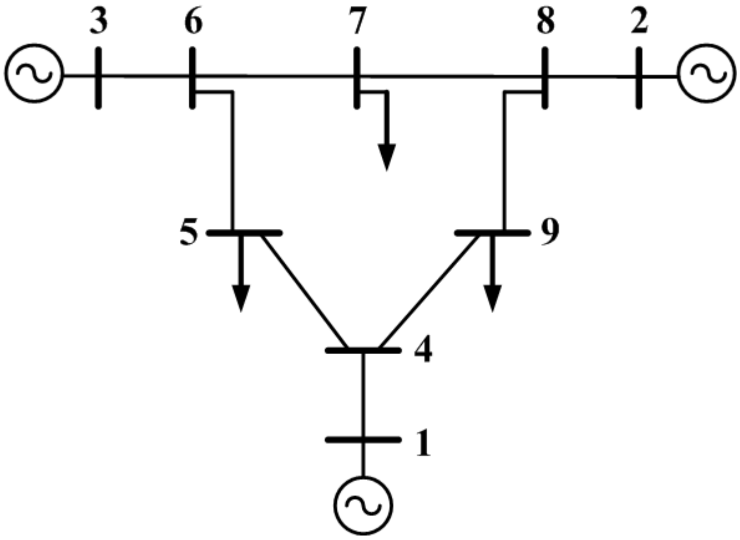
Qualification Strategy

Two test specifications will be implemented: one for verifying the FFR and SI control in case of the power converter is independent from other components and one for the verification of the OuI in case of interaction with other grid components and validation of the power system stability.

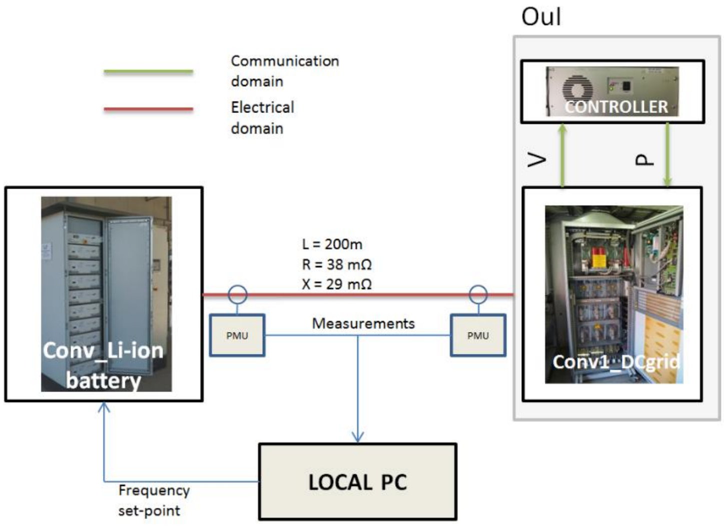
Test Specification TC14.TS1

Reference to Test Case	*TC14*
Title of Test	Synthetic inertia and fast frequency response/control provided by converter-based resources: *validating the FFR and SI control*.
Test Rationale	The validation of the FFR and SI control allows to evaluate the ability of the converter to provide these functions, considering also the variability attributes (Frequency variation, power set-point, voltage and current harmonics, measures accuracy).
Specific Test System (graphical)	This TS requires a grid simulator and one power converter with the OuI.
Target measures	Power and frequency measures time series of the power converter under test.
Input and output parameters	Frequency set-point, FCR, FFR and SI control mode ON/OFF, Power baseline.
Test Design	A simulation and/or a pure hardware experiment can be performed. A Pure hardware experiment is recommended but, with some assumption, also a simpler experiment can be performed. The test design for verifying the PoI 1 is the following: • Set the starting frequency to the grid simulator and the power baseline to the power converter. • Change the frequency (with a fixed ramp rate and amplitude) and log the power converter measurements. • Repeat the previous step until quality attributes will be achieved.
Initial system state	Frequency: 50 Hz Power baseline: at least three different initial states; one with lower power exchange, one with medium power exchange and one with high power exchange.
Evolution of system state and test signals	From 50 Hz up to 51.5 Hz, then down to 47.5 Hz with different step size (0.1 Hz, 0.25, 0.5 Hz).
Other parameters	See variability attributes.
Temporal resolution	At least 0.1 ms.
Source of uncertainty	Measures accuracy in case of non-simulation experiments.
Suspension criteria / Stopping criteria	Disconnection of the power converter.

Test Specification TC14.TS2

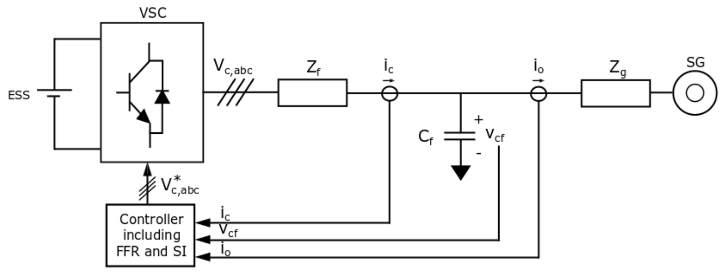
Reference to Test Case	*TC14*
Title of Test	Synthetic inertia and fast frequency response/control provided by converter-based resources: power system stability assessment.
Test Rationale	The test aims to verify that power converters limit the ROCOF and the frequency deviation considering also the variability attributes (Frequency variation, voltage set-point, voltage and current harmonics, measures accuracy, interaction between each power converter providing FFR and SI and other components, grid parameter, communication and controller delay).
Specific Test System (graphical)	IEEE 9 bus 
Target measures	Power and frequency measures time series of each power converter.
Input and output parameters	Production and consumption profiles, FCR, FFR and SI control mode ON/OFF, power baseline, number of power converters, mechanical inertia.
Test Design	The test design is the same of the TC14.TS1 but consumption and non-controllable production will be change instead of frequency.
Initial system state	Frequency: 50 Hz Power baseline: at least three different initial states; one with lower power exchange, one with medium power exchange and one with high power exchange.
Evolution of system state and test signals	Consumption or production change in order to have the same frequency variation of the TC14.TS1.
Other parameters	See variability attributes.
Temporal resolution	At least 0.1 ms.
Source of uncertainty	Measures accuracy in case of non-simulation experiments.
Suspension criteria / Stopping criteria	Disconnection of one or more components and/or frequency instability.

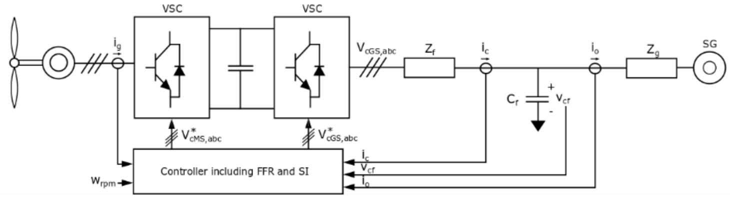
Experiment Specification TC14.TS1.ES1

Reference to Test Specification	*TS1*
Title of Experiment	*Pure Hardware test: validation of the FFR and SI functionalities of a power converter.*
Research Infrastructure	DER-TF (RSE, Milan)
Experiment Realisation	The power converter controller will be implemented on the DSpace controller that commands the power converter “Conv1_DCgrid”. The control functions are developed in Simulink. Another power converter “Conv_Li-ion battery”, connected to the “Conv1_DCgrid” through a line of 200 m, set voltage and frequency. No other electrical components are connected to this experiment setup. The voltage and current measurements are provided by two PMUs installed at the electrical output of each power converters. The power converter "Conv_Li-ion battery” will set different frequency values following the “Evolution of system state and test signals” description in TC14.TS1 with a pause between every change of about 20 s.
Experiment Setup (concrete lab equipment)	
Experimental Design and Justification	The Pure Hardware experiment aims to validate the ability of the power converter “Conv1_DCgrid” to provide FFR and SI functionalities considering the real behavior of a controller and a power converter of medium size (100 kVA).
Precision of equipment and measurement uncertainty	PMU uncertainties: u(I) = 1.5 A; u(V) = 1 V; u(f) = 5 mHz. Power converter precision: 0.5 V; 0.01 Hz.
Storage of experiment data	Data are collected on a local PC on a txt file every second with a sample time of 0.1 ms.

Experiment Specification TC14.TS1.ES2

<table>
<tr><td>Reference to Test Specification</td><td>TS1</td></tr>
<tr><td>Title of Experiment</td><td>Pure simulation test: Simulation for the validation of FFR and SI functionalities of converter-based resources: Dynamic response and stability assessment</td></tr>
<tr><td>Research Infrastructure</td><td>Tecnalia</td></tr>
<tr><td>Experiment Realisation</td><td>
Simulation model of grid connected power-electronics interfaced renewables and/or stationary battery energy systems following the schemes drafted in the figure below will be developed.





Two types of simulation studies will be performed:
i) <u>Dynamic simulations</u>
The objective of these simulations is to test the dynamic response of converter-based resources with FFR and SI functionalities under frequency deviations.
The frequency of the grid will be changed following a profile similar to that of the test signals for frequency injection described in previous work[4].
The current, voltage and power profiles of the power converter will be recorded and compared against those specified in the grid codes listed in the FuI of TC14.
ii) <u>Stability due to converter interactions</u>
One of the key issues in converter-dominated power systems are the interactions that can take place between the converter's controllers, filters, generators and the transmission network. If these interactions are not properly damped can lead to undamped oscillatory modes that make the system unstable. Identification of critical oscillatory modes and their dependence and sensibility to the converter and transmission system parameters will be addressed in this study. Combination of active damping schemes together with FFR and SI functionalities will be analyzed.
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<tr><td>Experiment Setup
(concrete lab equipment)</td><td>Simulations in Matlab/Simulink</td></tr>
<tr><td>Experimental Design and Justification</td><td>This simulation analysis aims to validate the operation of the controllers to provide FFR and SI functionality of converter-</td></tr>
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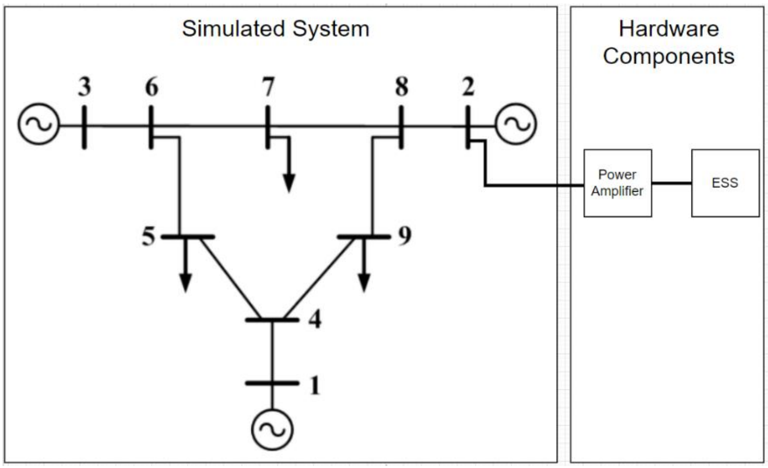
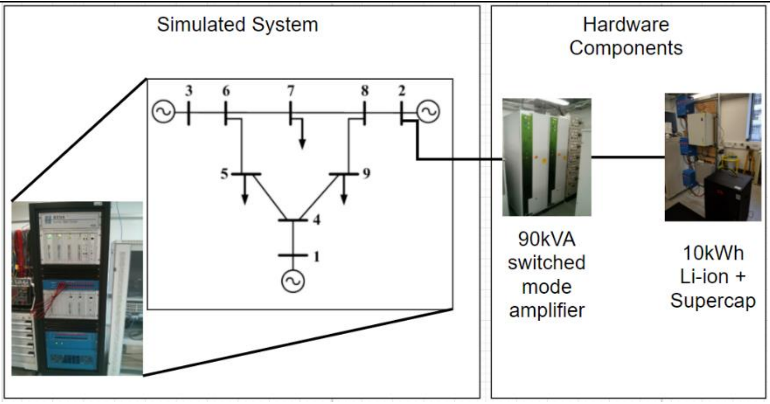
4 https://www.svk.se/siteassets/aktorsportalen/tekniska-riktlinjer/ovriga-instruktioner/technical-requirements-for-fast-frequency-reserve-provision-in-the-nordic-synchronous-area-1.pdf

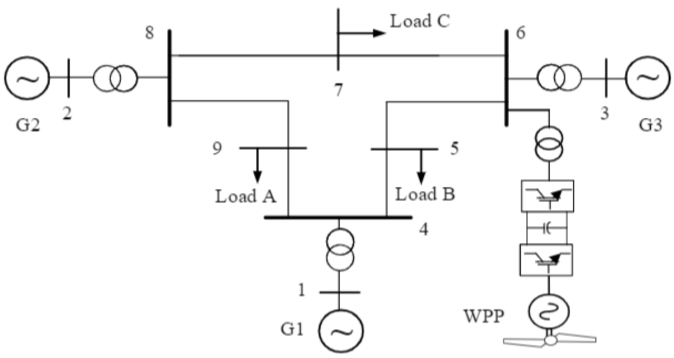
	based resources. Unitary converter validation is performed. It can be used as a reference for comparison with the hardware test validation in TC14.TS1.ES1 and as a preliminary stage before addressing power system stability assessment in TC14.TS2.ES2.
Precision of equipment and measurement uncertainty	Pure simulation analysis. Not applicable.
Storage of experiment data	Data is collected in a workspace while simulation is running and recorded in a local PC.

Experiment Specification TC14.TS2.ES1

Reference to Test Specification	*TS2*
Title of Experiment	*PHIL simulation for frequency stability assessment of renewable-based systems using SI and FFR support from converter-based resources*
Research Infrastructure	UST
Experiment Realisation	In this case a PHIL experiment is implemented for a more realistic assessment of the response of the converter interface resource to fast frequency changes. For consistency purposes, the same reference model (IEEE 9 bus) as used for the pure simulation experiment is simulated. This model is complemented with the addition of a converter interfaced hardware resource (in this case an ESS but could be of other type if required) in which the algorithms of SE and FFR will be implemented.  Different disturbances such as load increase or SG trip are carried out to evaluate ROCOF and frequency deviation of the system with SI/FFR in services.

Experiment Setup (concrete lab equipment)	 For the experimental setup an RTDS is used for the running the real-time simulation model, this will be coupled to the hardware under test through a PHIL interface composed of a 90kVA switched mode amplifier which communicates with the RTDS through analog or digital communications. The HUT is formed by a hybrid energy storage system with a 10kWh Li-ion battery and a supercapacitor.
Experimental Design and Justification	The PHIL experiment objective is to validate the stability of the system when the real hardware providing fast frequency support is interacting with the rest of the power system. By performing this experiment, possible issues introduced by the dynamics of the real hardware and the interactions between devices in the system are identified.
Precision of equipment and measurement uncertainty	
Storage of experiment data	Data will be collected at different locations (both in hardware and simulation) with a sufficient sampling rate to allow the identification of problems.

Experiment Specification TC14.TS2.ES2

Reference to Test Specification	*TS2*
Title of Experiment	*Pure simulation test: frequency stability assessment of renewable-based systems using SI and FFR support from converter-based resources*
Research Infrastructure	DTU
Experiment Realisation	Simulation:  IEEE 9 bus system with converter-based resources (CBR) (wind, PV, battery, etc.) as replacements for SGs is implemented in digital real-time simulator. CBRs are equipped with

	SI/FFR control based of specifications of grid codes. Different disturbances such as load increase or SG trip are carried out to evaluate ROCOF and frequency deviation of the system with SI/FFR in services. A delay can be added to emulate the communication latency. Comparison of SI/FFR based on different grid codes for frequency stability improvement. The interaction of SI/FFR of converters with SGs is also considered.
Experiment Setup (concrete lab equipment)	Pure simulation in RTDS
Experimental Design and Justification	*The pure simulation aims to evaluation frequency stability with SI and FFR support from converter-based resources in terms of ROCOF and frequency deviation.* *It can be a reference for a comparison with the PHiL simulation*
Precision of equipment and measurement uncertainty	PB5-based RTDS racks Time step of simulation: 50-60 µs
Storage of experiment data	Data is collected on run time of simulation in CSV extension file and stored at a local PC