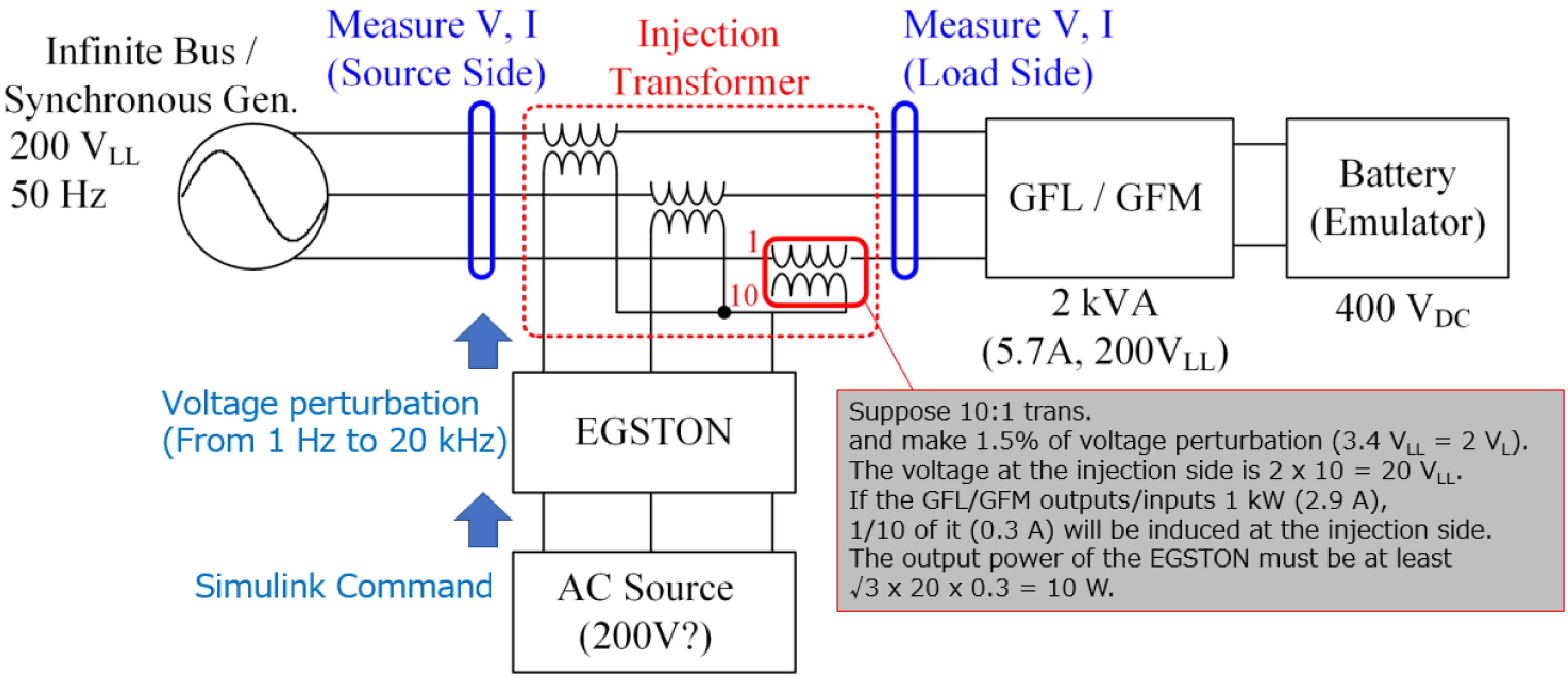
TITLE: Study of innovative impedance-based stability analysis for the power systems composed of inverter-based resources	AUTHOR: Yuko Hirase DATE: 19th November 2022

Object under Investigation (*OuI*)	Test Objectives	System under Test (*SuT*)
"The component(s) (1..n) that are to be qualified by the test" In the entire power system 1. impedance at each point of the transmission line 2. natural frequencies between power sources and between a power source and a load	Why is the test needed? What do we expect to find out? This study will demonstrate a new data driven-based grid stability analysis method using the impedance measured. It will be possible to accurately predict the impact of disturbances caused by power electronics equipment on power system stability and improve its dynamic characteristics, thereby increasing the resilience of the power system. The objective of this study is to obtain agreement between experimental results on this new impedance-based analyses and controls and preliminary studies based on mathematical theories and numerical simulations. It will be possible to protect the intellectual property of equipment manufacturers and power transmission and distribution companies while maintaining stability in the power systems of the near future, where large numbers of power electronic devices will be connected. On the other hand, many power-electronic devices connected to modern power grids are equipped with advanced control methods to actively stabilize the power system, such as virtual synchronous generator (VSG) (virtual synchronous machine: VSM) control. Power systems to which many devices with such advanced control are connected contain resonance points in various frequency bands, and more accurate impedance measurement is required. In addition, capacitance components of the line and equipment cannot be ignored, and the difficulty of impedance measurement increases in the same way. Therefore, one of the goals of this demonstration test is to reproduce such a recent power system more faithfully and to improve the accuracy of its analysis.	Systems, subsystems, components included in the test case or test setup Assume a two-machine system or a one-machine and one-load system. The machines connected to the system are an IBR (2 kVA, 200 VII) and an SG (2 kVA, 200 VII). The loads connected to the system is a three phase rresistive load (1 kVA, 200VII). All equipment will be current SINTEF equipment. An injection power supply that injects a series voltage perturbation or shunt current perturbation between the power supply and the load or between the power supplies is used. The power amplifier used in EGSTON can be applied for the injection power source. In the case of a voltage perturbation, the injection transformers (1:10, 20 A) are used, and in the case of a current perturbation, the injection reactors (4 mH) are used. Perturbation signals programmed by MATLAB/Simulink are sent to EGSTON, and the measurement of voltage and current on both sides of the perturbation is done using the communication function of EGSTON. The impedance is analysed offline by the MATLAB program from the stored measurement logs.
Function(s) under Investigation (*FuI*) "The referenced specification of a function realized (operationalized) by the object under investigation" To investigate the natural frequencies at various points in the power system where multiple power sources and loads are connected. Include high frequency bands not covered in previous studies, especially to find resonance frequencies caused by IBRs. Establish a new experimental method to replace the error-prone current perturbation method with a new evaluation method, the voltage perturbation method.	**Purpose of Investigation (*PoI*)** The test purposes classified in with terms *Characterization*, *Verification*, or *Validation*	**Functions under Test (*FuT*)** Functions relevant to the operation of the sys-

Domain under Investigation (*DuI*): "The relevant domains of test parameters and connectivity" The trajectory of natural frequencies is obtained by changing the tidal currents at equilibrium, the control variables of the IBR, and the location of the perturbation injection.	Characterize the stability at various points in the power system by natural frequencies and resonant frequencies between devices. Verify test results by checking agreement with previously prepared numerical simulations. Check the agreement with the results of small-signal analysis using the mathematical model and evaluate the validity. (However, if the equipment configuration is complex, the mathematical model should be simplified.)	tem under test, including FuI and relevant interactions btw. OuI and SuT The parameters of the power supply should be adjusted as much as possible so that the frequency of the target system is at the rated frequency. However, in an ideal measurement environment, changes in the amplitude of the perturbation voltage will not affect the impedance inherent in the target system.
Target metrics (*TM*) Measures retrievable from SuT required to quantify each of the identified test criteria Split the power system into source and load on either side of the point where the perturbation is injected. Voltage perturbations from 0.1 Hz to 10 kHz are injected into the d- or q-axis of the target power system in the synchronous reference frame. Measure the voltage and current on the source and load sides of the perturbation injection point, respectively, and calculate the 2x2 dq impedance matrix on the synchronous reference frame from these measurements. Calculate the loop impedance from the source and load impedance matrices and investigate its eigenvalue trajectory of the loop matrix.	**Test criteria** (*TCR*) Formulation of criteria *for each PoI* based on properties of SuT; encompasses properties of test signals and output measures The objective is to understand from the mathematical model that the resonant frequency of the system, calculated from the measured impedance, is due to system parameters, and to reproduce this oscillation in the time response of the simulation. We aim to match the trend of the eigenvalue trajectories calculated from the impedances measured from both the simulation and the demonstration tests, and to match the arrangement of the unstable poles. **Quality attributes** (*QA*) Threshold levels for test result quality as well as pass/fail criteria The objective of this study is to establish a measurement method to experimentally obtain a wide range of natural frequencies of IBR-based power systems. The acceptance criterion is that the corresponding natural frequencies are obtained by comparison with the results of prior numerical analysis and small-signal mathematical analysis, and the eigenvalue trajectories have the same tendencies between the simulation and the actual tests.	**Variability attributes** (*VA*) Identify relevant controllable or uncontrollable factors of the SuT and their required variability; refer to PoI Magnetic saturation of the transformer is more likely to occur in the low-frequency range and, conversely, the impedance of the transformer increases in the high-frequency range. Magnetic saturation can be avoided by using a transformer with a larger rating or maintaining the output of the injection power supply at the desired value (around 1% of the system voltage of 200 V). However, there may be measurement limitations with common commercial transformers, and we plan to identify measurement limitations using commercial transformers in this project. In addition, the data acquisition delay due to EGSTON communication may not be negligible in the measurement of impedance when high-frequency perturbations are injected. We also plan to clarify the demonstration limit frequency for the existing equipment.



Infinite Bus /
Synchronous Gen.
200 V_{LL}
50 Hz
Measure V, I
(Source Side)
Injection
Transformer
Measure V, I
(Load Side)
1
10
GFL / GFM
Battery
(Emulator)
2 kVA
(5.7A, 200V_{LL})
400 V_{DC}
Voltage perturbation
(From 1 Hz to 20 kHz)
EGSTON
Simulink Command
AC Source
(200V?)
Suppose 10:1 trans.
and make 1.5% of voltage perturbation (3.4 V_{LL} = 2 V_L).
The voltage at the injection side is 2 x 10 = 20 V_{LL}.
If the GFL/GFM outputs/inputs 1 kW (2.9 A),
1/10 of it (0.3 A) will be induced at the injection side.
The output power of the EGSTON must be at least
√3 x 20 x 0.3 = 10 W.