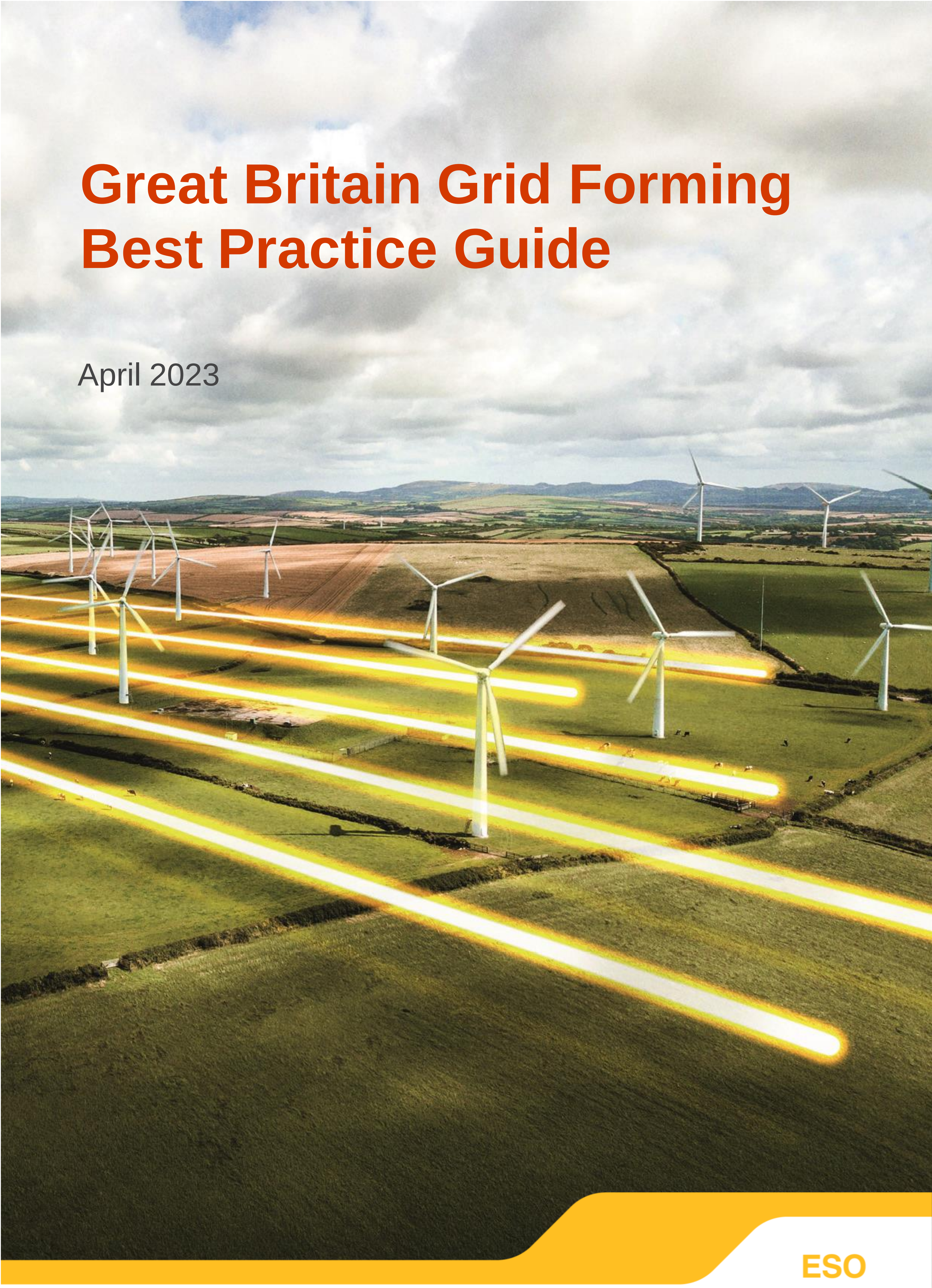
Great Britain Grid Forming Best Practice Guide

April 2023



1 Contents

Acknowledgements

Whilst this GB Grid Forming Best Practice Guide is published by Electricity System Operator (ESO), it wouldn't have been possible without collaboration with the organisations listed below. We would like to acknowledge and express our great appreciation for their invaluable contributions and feedback during the development stages of this GB Grid Forming Best Practice Guide.

Aalborg University

Amprion

ARUP

BP

Cardiff University

Carlton Power

Cornwall Energy

Drax

Edf Energy

Eleceffic

Enercon

Enstore

Energy Systems Integration Group (ESIG)

Field Energy

GE Grid Solutions

GE Renewable Energy

GE Vernova Energy Consulting

Global Power System Transformation (G-PST) Consortium

Highview Power

Hitachi Energy

Huawei Technologies

Imperial College London

KTH Royal Institute of Technology

National Grid Electricity Transmission

National Grid Ventures

National Physical Laboratory (NPL)

National Renewable Energy Laboratory (NREL)

NR Electric

ORE Catapult

Ørsted

Power Electronics

Red Eléctrica

RES Group

RWE

(Acknowledgements - Continued)

ScottishPower Renewables

Sembcorp

Shell

Siemens Energy

Siemens Gamesa Renewable Energy

Siemens PTI

SMA Solar Technology AG

SolarEdge

SP Energy Networks

SSEN Transmission

SSE Renewables

Swansea University

The National HVDC Centre

Uniper Technologies

University of Birmingham

University of Strathclyde

Urdal Power Solutions

Vattenfall

Vestas

WSP

Executive Summary

The GB Grid Forming (GBGF) Best Practice Guide aims to help relevant stakeholders (e.g. developers, manufacturers) understand generic requirements for implementation of GBGF applications within the GB electricity system.

For the avoidance of doubt, this GBGF Best Practice Guide should be used in conjunction with the Grid Code (GC) and supporting information developed through Grid Code modification GC0137 “Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability” rather than as a standalone document.

To avoid duplication with the GC0137 final modification report & annexes as well as other relevant documented guidance, this GBGF Best Practice Guide is structured as follows:

a) Chapter 2 evaluates the capabilities of multiple existing and emerging analysis tools for GBGF plants’ compliance testing purpose.
b) Chapter 3 discusses generic modelling requirements for GBGF-oriented analysis tools and typical operational modes of GBGF-I controllers against normal and abnormal operational conditions.
c) Chapter 4 discusses some key definitions for GBGF-Inverter (GBGF-I) plants.
d) Chapter 5 suggests some testing examples as relevant to compliance requirements of Active ROCOF Response Power, Active Phase Jump Power and Active Damping Power as defined in GC0137 Legal Text. Some further considerations are also discussed for compliance tests of Active Phase Jump Power under extreme conditions and during a faulted condition.

At end of each chapter as mentioned above, a table of potential future Grid Code modifications, as identified at the GBGF Best Practice Group, are proposed in order to facilitate future GB Grid Forming applications.

In line with key findings/suggestions of this GBGF Best Practice Guide, ESO proposes to progress the Grid Code modifications required for GB Grid Forming in stages reflecting the varying levels of urgency and effort required to complete the Grid Code changes beginning in Q2 2023.

Abbreviations

AC	Alternating Current
CCM	Component Connection Method
DRC	Data Registration Code
DC	Direct Current
ECC	European Connection Conditions
ECP	European Compliance Process
EMT	Electro-Magnetic Transient
ESIG	Energy Systems Integration Group
ESO	Electricity System Operator
FACTS	Flexible AC Transmission System
FFC	Fast Fault Current
FRT	Fault Ride Through
FSM	Frequency Sensitivity Mode
GBGF	Great Britain Grid Forming
GBGF-I	Great Britain Grid Forming - Inverter
GBGF-S	Great Britain Grid Forming - Synchronous Generator
GB	Great Britain
GD	Glossary & Definition
GFL	Grid Following
GFM	Grid Forming
HIL	Hardware-in-the-Loop
HVDC	High Voltage Direct Current
IBR	Inverter-Based Resource
IEEE	Institute of Electrical and Electronics Engineers
I/O	Input/Output
IVS	Internal Voltage Source
LFSM	Limited Frequency Sensitivity Mode
LTI	Linear Time-Invariant
NFP	Network Frequency Perturbation
NREL	National Renewable Energy Laboratory
OC	Operating Code
PART	Phase Angle Ride Through
PC	Planning Code
PLL	Phased Locked Loop
PSS	Power System Stabiliser
pu	Per Unit
RMS	Root Mean Squared

ROCOF	Rate of Change of Frequency
SoW	Scope of Work
STATCOM	Static Synchronous Compensator
TIV	Transient impedance value
ToR	Terms of Reference
TSO	Transmission System Operator
V2G	Vehicle-To-Grid

1. Introduction

1.1. Background

This Great Britain Grid Forming (GBGF) Best Practice Guide is produced by Electricity System Operator (ESO) in collaboration with external stakeholders in the UK and across the world to ensure a workable standard to facilitate Grid Forming applications within GB energy markets.

This GB Grid Forming Best Practice Guide aims to;

a) Provide the necessary guidance on the existing Legal Text following Grid Code Modification GC0137 “Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability” as shown on the ESO’s Grid Code Issue 6 Revision 16 as published on 5th January 2023.
b) Appropriately capture a set of good practices and suggestions from a wide range of members of the GBGF Best Practice Group for future GB Grid Forming development.
c) Identify any potential Grid Code modifications required to facilitate future GB Grid Forming applications.

1.2. Scope of Work

This GBGF Best Practice Guide document is to be used as guidance on achieving compliance with the key Grid Code obligations for Grid Forming within the GB Market. This does not override any obligations within Grid Code and should be used in conjunction with the codes as a Best Practice Guide on how to achieve compliance with the code requirements.

This GBGF Best Practice Guide will be evolved over time as Grid Forming technology develops and following the developments of ESO’s documented consultations with wider stakeholders and future Grid Code modifications where appropriate.

1.3. References

[1] ESO, Grid Code (GC) Issue 6 Revision 16, 5 January 2023.
URL: https://www.nationalgrideso.com/document/162271/download

[2] GC0137 Modification Report and Annexes.
URL: https://www.nationalgrideso.com/document/220516/download

2. Analysis Tools for Compliance Testing

2.1. Introduction

This Chapter provides guidance on the most appropriate time-domain non-linear analysis tools (e.g. EMT and RMS) and/or linear analysis tools (e.g. Network Frequency Perturbation (NFP) and Impedance Scan) as suggested for the series of tests listed in ECP Appendix 9 – Compliance Testing for Grid Forming Plant.

2.2. Non-Linear Time-domain Analysis Tools

2.2.1. EMT-based Analysis

The fundamental principle of EMT-based time-domain analysis tools always consider the instantaneous values of voltage and current, in contrast to those RMS-based ones where only the fundamental frequency values are considered. Typical simulation time-step for EMT simulation is 50 µs and smaller time-steps between 2-5 µs are used for simulating power electronic converters with high switching frequencies. In some black-box EMT models, high time resolution simulation of power electronics may be decoupled from the EMT simulation time step, thereby avoiding excessively small EMT simulation time steps with power electronics. This means that EMT simulations can be used for simulations of very high frequency phenomena such as lightning, switching surges and control system design/coordination of HVDC and FACTS devices.

Due to the features mentioned above, EMT simulations have become essential in analysing the dynamic behaviours of Grid Forming Plants under large disturbances such as system faults. The simulation studies focus on the following aspects but not limited to:

- Transient overvoltage or overcurrent
- Oscillations
- Control interactions between converters and/or between a converter and other power system components

For these types of studies, the Grid Forming Plant and relevant parts of a power network will be modelled in EMT simulation environment. Detailed time-domain analysis studies need to be carried out under large disturbances in the network.

Among various EMT simulation studies, a Real-Time EMT simulation facility offers additional features on different types of Hardware in the Loop (HIL) testing:

a) The power network and converters are simulated in the Real-Time EMT simulation facility while the control hardware is interfaced with it through I/O devices and amplifiers if applicable. This kind of study is used to test the performance of control hardware.
b) Part of the power network and converters are simulated in Real-Time EMT simulation facility and physical power devices (e.g. converters) under test are interfaced with it. This kind of study is used to test the performance of physical power devices.
c) The power network and converters are simulated in the Real-Time EMT simulation facility while the protection relays are interfaced with it through I/O devices and amplifiers if applicable. This kind of study is used to test the performance of protective relays during certain disturbances in a power network.

2.2.2. RMS-based Analysis

Besides EMT-based tools, the RMS-based analysis tools are also widely used for time-domain analysis. The fundamental difference between those two types of time-domain analysis tools is the instantaneous values of variables e.g. voltage/current are calculated in an EMT simulation by solving differential equations of dynamic models as represented for network components, whilst the fundamental frequency values are calculated in a RMS simulation as the variables are only represented by phasors.

Following such key difference, as mentioned in Section 2.2.1, the time step of an EMT simulation is usually around microseconds, whereas in an RMS simulation, it would typically be a few milliseconds. It means that, compared with the RMS-based tools, the EMT-based tools can achieve more accurate simulation results within a wider frequency range but requiring much more computational efforts.

In this way, when a trade-off between computational effort and simulation accuracy should be carefully considered, the RMS-based tools are more suitable for dynamic stability studies of large-scale power system around a fundamental frequency.

2.3. Linear Analysis Tools

2.3.1. Analysis Tool based on Network Frequency Perturbation (NFP)

Relevant Grid Code Clauses [1]:

GD - Network Frequency Perturbation Plot	A form of Bode Plot which plots the amplitude (%) and phase (degrees) of the resulting output oscillation responding to an applied input oscillation across a frequency base. The plot will be used to assess the capability and performance of a Grid Forming Plant and to ensure that it does not pose a risk to other Plant and Apparatus connected to the Total System. For GBGF-I, these are used to provide data to The Company which together with the associated Nichols Chart (or equivalent) defines the effects on a GBGF-I for changes in the frequency of the applied input oscillation. The input is the applied as an input oscillation and the output is the resulting oscillations in the GBGF-I's Active Power. For the avoidance of doubt, Generators in respect of GBGF-S can provide their data using the existing formats and do not need to supply NFP plots.
GD - Nichols Chart	For a GBGF-I, a chart derived from the open loop Bode Plots that are used to produce an NFP Plot. The Nichols Chart plots open loop gain versus open loop phase angle. This enables the open loop phase for an open loop gain of 1 to be identified for use in defining the GBGF-I's equivalent Damping Factor.
GD - Active Frequency Response Power	For GBGF-I this can rapidly inject or absorb Active Power in addition to the phase-based Active Inertia Power to provide a system with desirable NFP plot characteristics.
ECC.6.3.19.3 (v)	Each GBGF-I shall be capable of: (c) being designed so as not to cause any undue interactions which could cause damage to the Total System or other User's Plant and Apparatus.
ECP.A.3.9.2	d) A Network Frequency Perturbation Plot with a Nichols Chart demonstrating the equivalent Damping Factor.
ECP.A.3.9.3	For GBGF-I, the User or Non-CUSC Party may be required to supply other versions of the Network Frequency Perturbation Plot for different input and output signals as defined by The Company.
ECP.A.3.9.6	i) Demonstration of Damping by injecting a Test Signal in the time domain at the Grid Oscillation Value and frequency into the model of the GBGF-I. An acceptable performance will be judged when the result matches the

	NFP Plot declared by the Grid Forming Plant Owner as submitted in PC.A.5.8.1(i). ii) Test i) is repeated with variations in the frequency of the Test Signal. An acceptable performance will be judged when the result matches the NFP Plot declared by the Grid Forming Plant Owner as submitted in PC.A.5.8.1(i).
PC.A.5.8.1(i)	(i) Each GBGF-I shall be designed so as not to interact and affect the operation, performance, safety or capability of other User's Plant and Apparatus connected to the Total System. To achieve this requirement, each User shall be required to submit a Network Frequency Perturbation Plot and Nichols Chart (or equivalent as agreed with The Company) which shall be assessed in accordance with the requirements of ECP.A.3.9.3.

The NFP method fundamentally applies intentional perturbations on system frequency (e.g. through controllable grid emulators), enabling the Grid Forming Plant's characteristic to be reflected in the form of Bode Plot in response to different frequency perturbations [1][5].

The frequency of a source (e.g. a controllable grid emulator) can be modulated following (1):

$$f(t) = f_0 + \Delta f \cos(2\pi f_{mod} t) \tag{1}$$

where f_0 is the nominal frequency of the system, Δf is the magnitude of the frequency variation, and f_{mod} is the modulation frequency of the applied perturbation (all in Hz).

The Grid Forming Plant connected to the modulated source will response to the frequency perturbation with modulated active power which can be represented by (2):

$$P_o(t) = P_{ref} + \Delta P \cos(2\pi f_{mod} t + \emptyset_{\Delta P}) \tag{2}$$

It is assumed that the perturbation frequency magnitude (Δf) is sufficiently small, so the Grid Forming Plant can be treated as a linear system. The active power response (P_o) of the Grid Forming Plant can be recorded at each modulated frequency by varying modulation frequency. Through performing a Fourier Transformation of both amplitude (ΔP) and Phase Angle ($\phi_{\Delta P}$), the frequency-domain Magnitude and Phase of the resulting power perturbation can be adopted. For every frequency, it can produce a response with the same frequency, with a certain Magnitude of ΔP and Phase Angle of $\phi_{\Delta P}$. When repeating the tests at a range of perturbation frequency, a Bode Plot representing the characteristics of the Grid Forming Plant can be adopted. The response characteristic can be represented in (3):

$$Response = \frac{\Delta \mathrm{P} \angle \emptyset_{\Delta P}}{\frac{\Delta f}{f_0}} \tag{3}$$

Based on such basic principle, different solutions to production of NFP-based Bode plots and relevant analysis methods are suggested from multiple BPG contributors. Their reports with details are included in the Annexes of this GBGF Best Practice Guide [4][5].

2.3.2. Impedance-based Analysis Tool

Relevant Grid Code Clauses [1]:

ECC.6.3.19.3 (v)	Each GBGF-I shall be capable of: - (c) being designed so as not to cause any undue interactions which could cause damage to the Total System or other User's Plant and Apparatus.

The impedance-based methods and tools are suggested in [6]-[8] for the following areas of power system analysis, particularly considering for future high penetration of Inverter-based Resources (IBRs):

- Dynamic interaction among power grid and IBRs
- Control Interaction between IBRs as located in proximity to each other
- Damping of wide-area oscillation modes
- Frequency response

1) Key principle - matrix form of impedance of power converters

The impedance of power converters can be represented in either *d-q* frame or Stationary Frame (α-β), which are mathematically equivalent [9]-[11]. Their general representations can be given by

$$\begin{bmatrix} v_d(s) \\ v_q(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} i_d(s) \\ i_q(s) \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} v_{\alpha\beta}(s) \\ v_{\alpha\beta}^{*}(s-2j\omega_0) \end{bmatrix} = \begin{bmatrix} Z_{\alpha\beta 11}(s) & Z_{\alpha\beta 12}(s) \\ Z_{\alpha\beta 21}(s) & Z_{\alpha\beta 22}(s) \end{bmatrix} \begin{bmatrix} i_{\alpha\beta}(s) \\ i_{\alpha\beta}^{*}(s-2j\omega_0) \end{bmatrix} \tag{5}$$

It is known from (4)-(5) that regardless of the selected frame, the impedance of power converters always has a 2 by 2 matrix representation. Hence, the accurate impedance measurement should measure all 4 elements in the impedance matrix [9]-[11].

2) Considerations of impedance measurement of power converters

Figure 1 shows the configuration of the impedance measurement of power converters, where the impedance measurement toolbox is inserted between the power converter and the AC grid. By injecting a voltage (current) perturbation at the ac terminals of the power converter, and measuring the corresponding current (voltage) response. The impedance of power converters can be calculated [10]-[12].

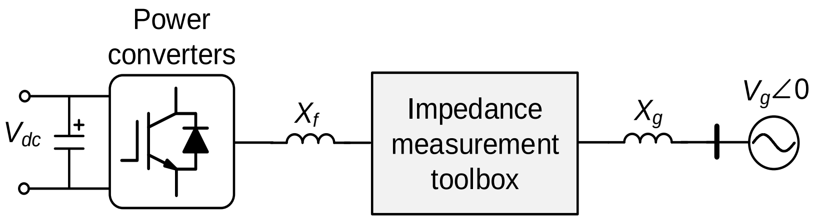


Figure 1: Configuration of Impedance Measurement of Power Converters (Source: Aalborg University).

Several considerations for impedance measurement are listed below:

a) Operating point dependent impedance matrix: The impedance matrix profile of power converters in the low-frequency range is highly dependent on its operating point [13]. Hence, for low-frequency stability analysis, e.g., sub-synchronous oscillation studies, the impedance measurement should cover different operating points of power converters (e.g. different *P*, *Q*, *V*, etc.). In contrast, the high-frequency impedance profile of power converters is less sensitive to its operating point variations. Therefore, for harmonic stability studies where the frequency range of interest is beyond several hundred Hz. The impedance measurement result based on single arbitrary operating points of the power converter can be used.

b) Impedance measurement of power converters under unstable operation: For a stable converter-grid system, the impedance matrix of the power converter can be directly measured by inserting toolbox between AC-terminal of the power converter and the AC grid, as shown in Figure 1. Yet, it is not feasible if the converter-grid system itself is unstable, as the impedance measurement can only be performed based on a stable case. In this scenario, we need to go through following 2 steps for the impedance measurement:
  - To perform power flow analysis to the original unstable converter-grid system and obtain the operating point of the power converter.
  - To create a stable case while keeping the operation point of the power converter to be the same as that obtained in Step 1.

Since the unstable operation of the converter-grid system is usually caused by the dynamic interaction between the power converter and the grid impedance, the simplest way to “create” the stable case is to connect the power converter to an ideal AC voltage source. It should be emphasized that the impedance matrix of the power converter is operating-point dependent, and hence, it is important to guarantee the same operating point when creating these stable cases.

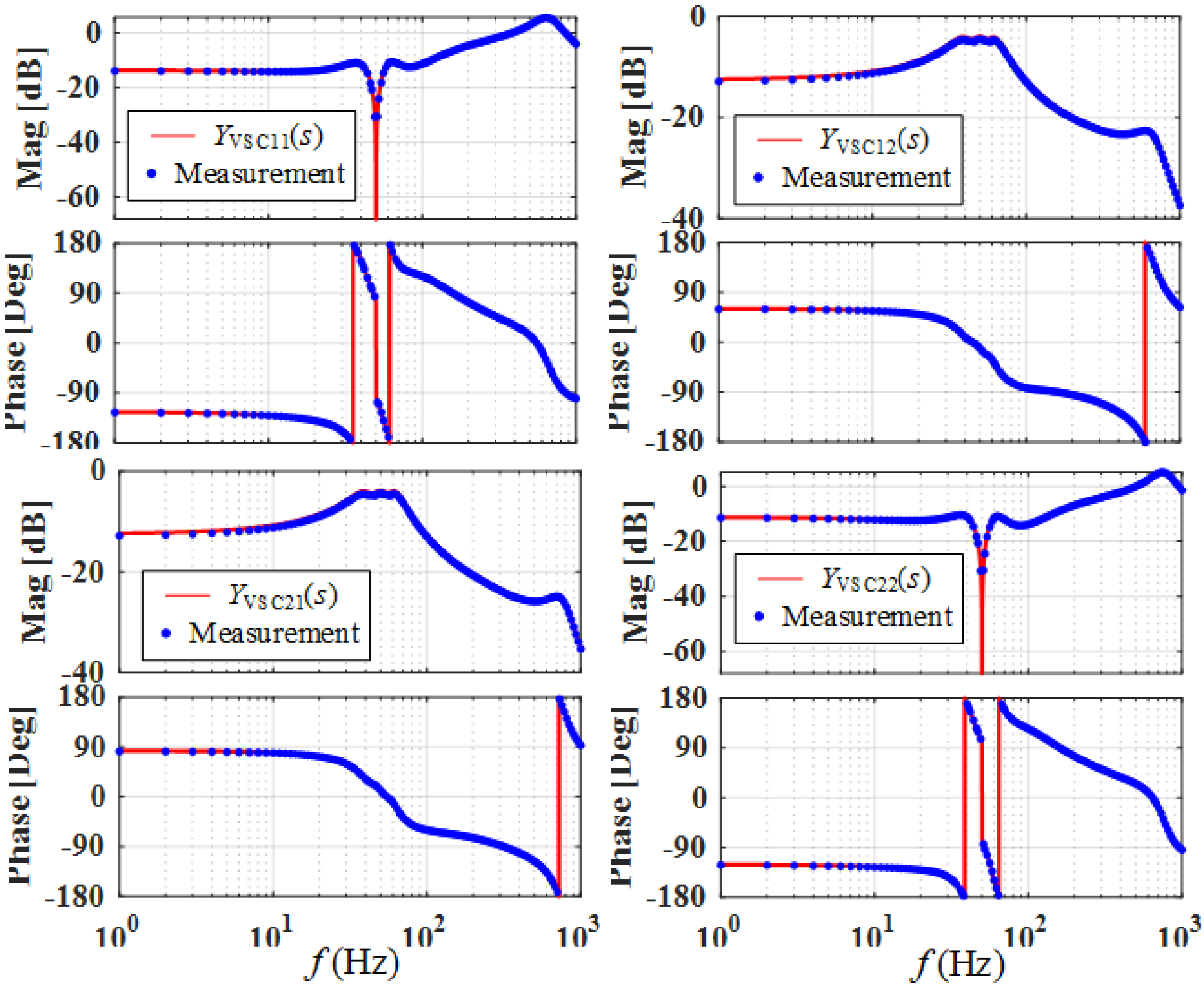


Figure 2: Impedance Measurement Results based on Automated Impedance Measurement (AIM) Toolbox (Source: Aalborg University).

3) Impedance measurement of power converters in real field

While there have been increasing research efforts made in academia to improve the accuracy of the impedance (matrix) measurement of power converters, the verifications of the proposed impedance measurement methods are often based on simplified converter-grid models, from which their effectiveness on the real-world project cannot be fully demonstrated. In recent years, there have been a few real-field impedance measurement demonstrations, below are some examples:

a) An example as suggested in [14]: The impedance measurement toolbox as developed is used for measuring the AC impedance matrix of the commercial wind turbine converter.
b) An example co-developed between academia and TSO: By collaborating with a European TSO, a BPG member has developed the EMT-compatible software toolbox for TSO's model validation and stability assessment [15], which can be used to measure the AC/DC impedance matrix of the vendor-specific HVDC [16][17]. Figure 2 shows the measurement results. More details of the toolbox can be found in [15].

4) Comparisons of Impedance-based example results between GFL and GFM Converters

The frequency-domain impedance measurements from physical IBR plants and/or impedance scan tools based on offline EMT and HIL are effectively applied for dynamic studies of Grid Following (GFL) based IBRs. The examples of such impedance-based measurements and tools are illustrated for GFL-based IBRs in [8]. Those study results can help manage risks of introducing new GFL-based IBRs in proximity to other IBRs and/or network devices in the same area e.g. interactions as well as impacts of oscillations in wider areas [8].

Similarly, such impedance methods can be rolled out for Grid Forming (GFM) based IBRs as well. An example for the admittance spectrum in *d-q* frame (Y_{dd}) for GFM and GFL converters is illustrated in [19] with testing parameters in Table 1 [18].

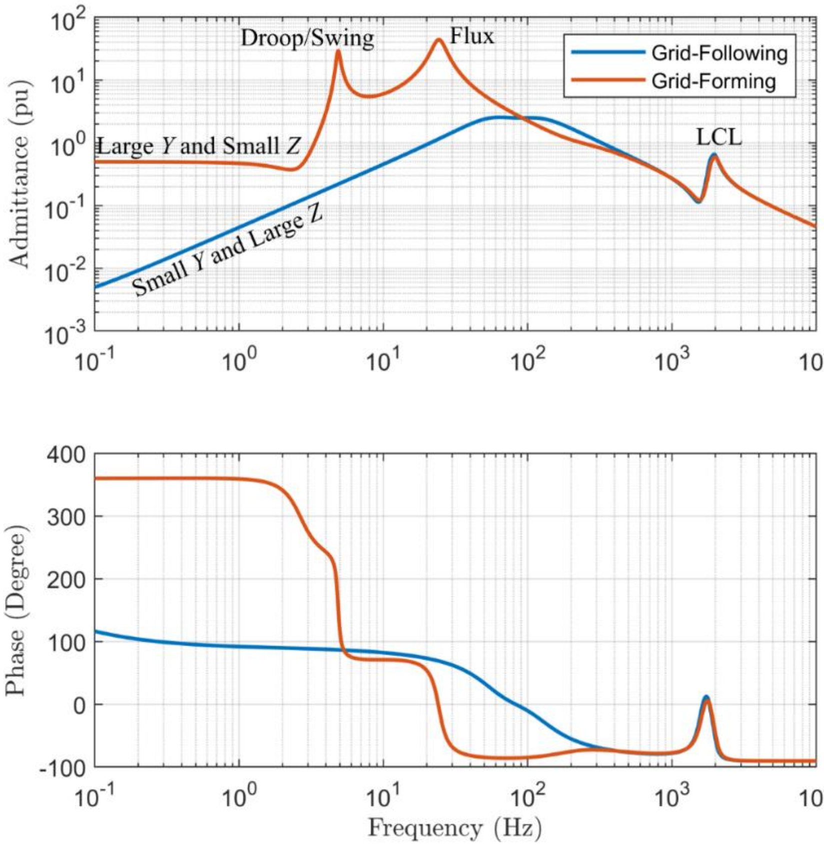
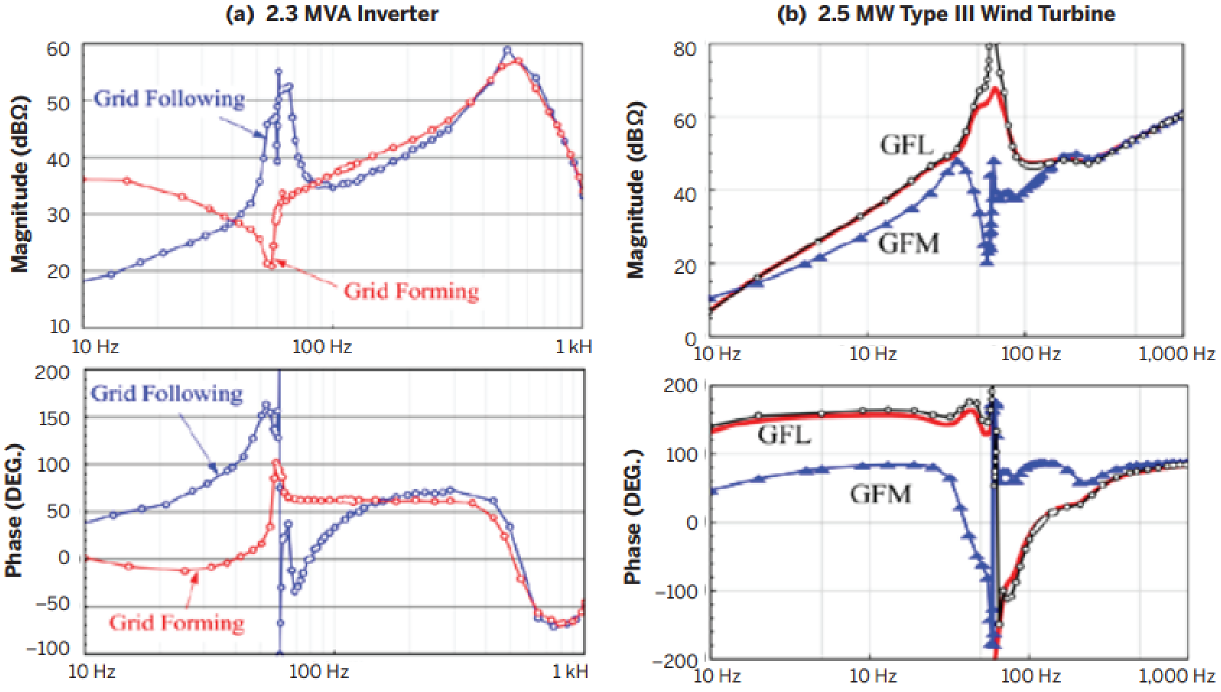


Figure 3: Comparison between Admittance Characteristics of GFL and GFM IBR Plants (Source: Imperial College).

Table 1: Parameters for Impedance-base Testing for GFL and GFM Converters (Source: Imperial College)

LCL filters:	
Converter side filtering inductor L_f	0.05 pu
Filtering capacitor C_f	0.02 pu
Grid side coupling inductor L_c	0.01 pu
Line inductor L_l	0.1 pu
The inner resistance of all inductors is selected based on *X/R*	10
GFM controller:	
Droop gain	0.1 pu
Droop bandwidth	0.5 Hz
Ideal voltage bandwidth	300Hz
GFL controller:	
PLL bandwidth	10 Hz
Ideal current bandwidth	300 Hz

As illustrated in [6], [20] and [21], Figure 4 shows study results of positive-sequence impedance response of the 2.3 MVA hardware inverter and the EMT model of 2.5 MW Type III wind turbine, operating in both control modes of GFL and GFM.


(a) 2.3 MVA Inverter

(b) 2.5 MW Type III Wind Turbine

Figure 4: Positive Impedance Measurement for GFM and GFL IBRs (Source: NREL).

A key observation from Figure 3 and Figure 4: Compared with GFL converters, the impedance magnitude of the GFM converters can be much lower (admittance magnitude is much higher) around the fundamental frequency (in Stationary Frame) due to different typical characteristics of GFL mode (as a Current Source) and GFM mode (as a Voltage Source).

In addition, the positive damping characteristics of the GFM converters can be learnt from Figure 4. Due to their phase angles vary within the range between -90 degrees to +90 degrees. Such damping characteristics can be quantified via impedance-based tools as suggested in [6].

As also suggested in [6], a frequency scan method can be used to test a GFM converter's frequency response. Such test aims to measure the Transfer Function from the GFM converter's active power output to the frequency of its terminal voltage. The low frequencies up to a few tens of are considered for implementation of such frequency scan test [21]. An example of such impedance-based tools for frequency response testing is illustrated in Figure 5 based on simulation models as well as physical device (a physical 2 MW synchronous generator using a grid simulator) [6][23]:

a) The primary frequency response can be measured via the DC gain of the transfer function at low frequencies.
b) The inertia (instantaneous active power response) can be measured via capacitive response.

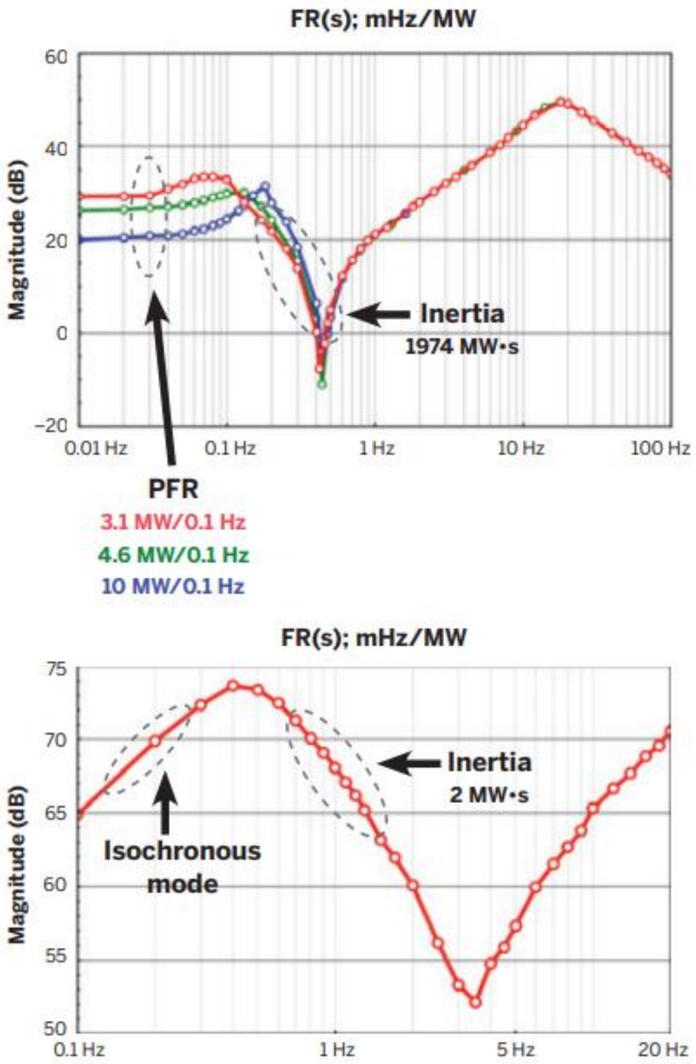


Figure 5: Frequency Scan Method for Estimating the Inherent Active Power Response, Damping, and Frequency Responses of Generators (Source: NREL)

2.3.3. Eigenvalue Analysis Tool

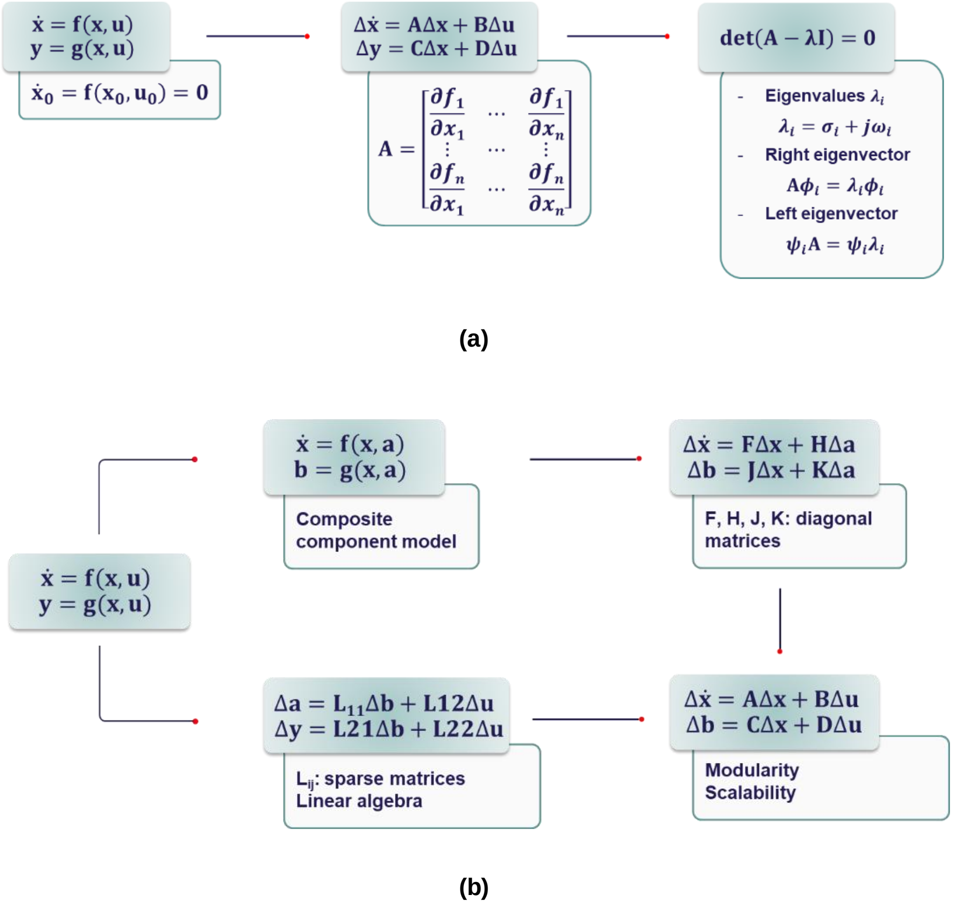
The eigenvalue analysis is a common practice for analysing the small-signal stability of power systems. The method is based on the state-space model of the system, whose linearised form is given by

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \tag{6}$$

where *A*, *B*, *C*, *D* are time-invariant coefficient matrix for a Linear Time-Invariant (LTI) system, and the eigenvalues of the state matrix *A* can be derived by

$$\det(sI - A) = 0 \tag{7}$$

which is also the characteristic equation of the LTI system. The eigenvalues indicate dynamic modes of the power system. The right eigenvector depicts the distribution of system modes through state variables, and the left eigenvector identifies the relative effects of initial conditions of state variables on system modes. The combination of these two eigenvectors leads to the participation factor, which weighs the contribution of state variables to system modes. Hence, the state-space modelling and analysis not only characterise the input-output stability of the system but give a global view on system oscillation modes and the contributions of state variables to those modes.



(a)

(b)

Figure 6: Comparison Between the Modelling Procedures of the General State-Space Representation and Component Connection Method (CCM). (a) General State-Space Model. (b) CCM-Based Model – Source: Aalborg University.

For legacy power systems, the small-signal stability is mainly governed by the electromechanical dynamics of synchronous generators. The electro-magnetic transients of power networks are often overlooked, except the study of sub-synchronous resonances. The well-decoupled timescales of generator- and network-dynamics facilitates using the closed-form eigenvalue analysis for large-scale power grids. Nevertheless, the small-signal stability of power-electronic-based power systems features multi-timescale and frequency-coupling dynamics, which may lead to oscillations in a wide frequency range. The wide-timescale dynamics of power converters are tightly coupled with that of power networks, leading to a high-order system state matrix and consequently imposing a high computational burden for the stability analysis.

To address the high computational demand, the Component Connection Method (CCM) was reported for converter-based power grids, and it features a computationally efficient procedure for deriving the state-space model given in (6). Figure 6 shows a comparison between the procedures of the general state-space modelling and the CCM [24]. In the CCM, the power system is first decomposed into multiple components, e.g. power converters, generators, and the power network, which are then interconnected by linear algebraic relationships defined by their interfaces. Next, the components are linearized locally, and their LTI state-space models constitute a composite component model. The CCM provides a modularised and scalable modelling framework, which is prominent for large-scale power systems. The algebraic interconnections of components significantly reduce the computational effort.

2.4. Summary of Proposed Analysis Tools for Compliance Testing

Following the introductions in Section 2.2 & 2.3 as well as discussion outcomes of GB Grid Forming Best Practice Group, the summary of multiple analysis tools are listed in Table 2 for a group of compliance tests in ECP.A.9.

Table 2: Summary of Proposed Analysis Tools for Compliance Testing*

Ref. No	Task	Clause in GC0137	Non-Linear Time-Domain Analysis Tools			Linear Analysis Tools		
			Offline EMT	RT-EMT	RMS	Eigen Value	NFP	Imp. based
1	Active ROCOF response power under extreme system frequencies	ECP.A.9.1.9.3	✓	✓				
2	Active ROCOF response power over full system frequency range	ECP.A.9.1.9.4	✓	✓			✓	✓
3	Active phase jump power under normal operation	ECP.A.9.1.9.5	✓	✓	✓			
4	Active phase jump power under extreme condition	ECP.A.9.1.9.6	✓	✓	✓			
5	Active phase jump power during a faulted condition for GBGF-I	ECP.A.9.1.9.7	✓	✓	✓			
6	Fault ride through during a faulted condition for GBGF-I	ECP.A.9.1.9.7	✓	✓				
7	Fast fault current injection during a faulted condition for GBGF-I	ECP.A.9.1.9.7	✓	✓				
8	Active Damping Power for GBGF-I	ECP.A.9.1.9.8	✓	✓		✓	✓	✓

Note*: For compliance purposes, where necessary and applicable, more than one tool can be selected to assist each other for validating performance of GBGF plants for specific compliance test. For example: EMT + Linear analysis tools for Item 8 in Table 2.

2.5. Suggestions for Further Grid Code Modifications

The key suggestions are captured by ESO in the Table 3 below following GB Grid Forming Best Practice Group discussions and data contributions from its Subgroup 2.

Table 3: Key Suggestions as Captured by ESO after consulting with GBGF BPG Members.

Key Suggestions	Priority for Grid Code Change**	Further Efforts during 2nd Round GC Mod. **	Comments
Existing and new linear analysis tools can be further validated as appropriate for the compliance test of GBGF-I's active damping power and other compliance testing purposes, as potentially identified by ESO in future, for GB Grid Forming Plant.	**Medium**	**Medium**	Further review and development, from a reasonable mix of subject-matter expert volunteers from industry and academia in UK and wider, can be considered during the 2nd Grid Code Modification Working Group collaboration for GB Grid Forming, developing detailed guidance on existing and proposed new linear analysis tools as appropriate to assist with relevant existing and emerging compliance tests as identified by ESO.

Note**:

Priority for Grid Code Change	Comment	Further Efforts during 2nd Round GC Modification	Comment
High	Such change is **urgent and important** for GBGF implementation	**High**	**Intensive efforts** are needed from Grid Code Modification Working Group to clearly understand a specific topic.
Medium	Such change is **important but not urgent** for GBGF implementation	**Medium**	**Certain efforts** are needed from Grid Code Modification Working Group to clearly understand a specific topic.
Low	Such change is **neither urgent nor important** for GBGF implementation	**Low**	**Minimal efforts** are needed from Grid Code Modification Working Group to clearly understand a specific topic.

2.6. References

[1] ESO, Grid Code (GC) Issue 6 Revision 16, 5 January 2023. URL: https://www.nationalgrideso.com/document/162271/download

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3. GBGF-I Modelling Requirements

3.1. General GBGF-I Modelling Requirements

3.1.1. Time-domain Modelling Requirements

The EMT-based non-linear models are used for evaluating fast electrical transients that involve high bandwidth controls of IBRs, such as grid faults (balanced and unbalanced), line switching, and electrical resonances. Those EMT models should include a detailed representation of the converter controls that participate in interactions with grid electrical transients, which may include at least the following elements

- Detailed inner control loops (e.g. current control and or voltage controls if used)
- Controller limits and rate limits
- Synchronising logic
- Active power, reactive power, voltage control loops
- DC Voltage controls
- Protection functions

Those EMT models should also include a representation of hardware components that impact interactions with the grid, which may include at least the following

- Transformers (including its saturation effect)
- DC Capacitance
- Passive harmonic filters
- Converter bridge model (averaged or switching model acceptable, but includes overmodulation effect)
- DC Chopper/dynamic brake

3.1.2. Frequency-domain Modelling Requirements

Frequency-domain linear models represent the small-signal characteristics of the plant at a given operating point. These models may be used to create transfer functions (magnitude and phase vs frequency) between key inputs and outputs of the plant. These models reflect equipment behaviour within a defined frequency range and when not operating in limits.

Frequency-domain models are used for evaluating small-signal stability aspects that involve the inverter-based resource controls and hardware together with the grid. Frequency domain models are derived based on a given initial operating condition of the system and small perturbation around that operating condition (such as small changes in grid frequency).

Frequency-domain models are provided in the following different formats:

- Frequency domain plots (or data) of magnitude vs. frequency and phase vs. frequency
- Simplified (“Open Box”) block diagrams

Frequency-domain models should be supplied together with documentation indicating the following:

- Range of operating points for which the model is valid
- Frequency range for which the model is valid (e.g. 0-20Hz)
- Definition of inputs and outputs and units
- Description of any assumptions or limitations of the model)

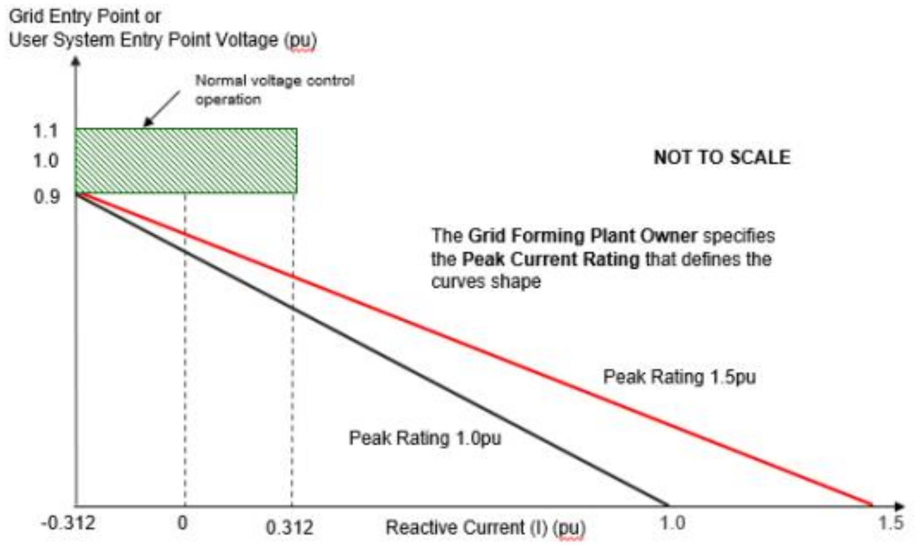
3.2. Operational Mode and Model of GBGF-I Control System

3.2.1. Introduction

This Section aims to find answers to the question raised during the GBGF Best Practice Group Discussion:

a) Is the “Linear Mode” is defined based on the voltage level, rather than the current limit level?
b) Instead of “Linear” and “Nonlinear” Modes, are there any more appropriate alternative definitions of operational modes e.g. “Normal Operation” and “Current-Limiting Operation”?

Relevant Grid Code Clauses [1]:

ECC.6.3.19.5.1	For any balanced fault which results in the positive phase sequence voltage falling below the voltage levels specified in CC.6.1.4 or ECC.6.1.4 (as applicable) at the Grid Entry Point or User System Entry Point (if Embedded), a Grid Forming Plant shall, as a minimum be required to inject a reactive current of at least their Peak Current Rating when the voltage at the Grid Entry Point or User System Entry Point drops to zero. For intermediate retained voltages at the Grid Entry Point or User System Entry Point, the injected reactive current shall be on or above a line drawn from the bottom left hand corner of the normal voltage control operating zone (shown in the rectangular green shaded area of Figure ECC.6.3.19.5(a)) and the specified Peak Current Rating at a voltage of zero at the Grid Entry Point or User System Entry Point as shown in Figure ECC.16.3.19.5(a). Typical examples of limit lines are shown in Figure ECC.16.3.19.5(a) for a Peak Current Rating of 1.0pu where the injected reactive current must be on or above the black line and a Peak Current Rating of 1.5pu where injected reactive current must be on or above the red line.
Figure ECC.6.3.19.5 (a)	 Figure ECC.6.3.19.5(a)
ECC.6.3.19.5.2	Figure ECC.6.3.19.5(a) defines the reactive current to be supplied under a faulted condition which shall be dependent upon the pre-fault operating condition and the retained voltage at the Grid Entry Point or User System Entry Point voltage. For the avoidance of doubt, each Grid Forming Plant (and any constituent element thereof), shall be required to inject a reactive current which shall be not less than its pre-fault reactive current and which shall as a minimum, increase each time the voltage at the Grid Entry Point or User System Entry Point (if Embedded) falls below 0.9pu whilst ensuring the overall rating of the Grid Forming Plant (or constituent element thereof) shall not be exceeded.

ECC.6.3.19.5.3	In addition to the requirements of ECC.6.3.19.5.1 and ECC.6.3.19.5.2, each Grid Forming Plant shall be required to inject reactive current above the shaded area shown in Figure ECC.6.3.19.5(b) when the retained voltage at the Grid Entry Point or User System Entry Point falls to 0pu. Where the retained voltage at the Grid Entry Point or User System Entry Point is below 0.9pu but above 0pu (for example when significant active current is drawn by loads and/or resistive components arising from both local and remote faults or disturbances from other Plant and Apparatus connected to the Total System) the injected reactive current component shall be in accordance with Figure ECC.6.3.19.5(a).

3.2.2. Normal System Operating Conditions for GBGF-I (Normal Mode)

The proposed normal operating conditions are:

- A voltage magnitude within the range defined in the Grid Code
- A voltage unbalance ratio within the range defined in the Grid Code
- A frequency within the range defined in the Grid Code of 47 Hz to 52 Hz
- A power factor within the range defined in the Grid Code
- Operating within the SQSS defined ROCOF rate of up to +/- 1 Hz / s
- Operating within the SQSS defined worst case +ve or -ve power transient
- Operating within a defined value for any AC Grid Phase Jump angle change

3.2.3. Abnormal System Operating Conditions for GBGF-I (Withstand Mode)

a) The AC Grid Short Circuit

This is the most common abnormal operating condition that only lasts for a short time of typically 140 ms in the GB Grid until the fault is cleared by the AC Grid's protection systems. The majority of the GB AC Grid remains in the normal operating condition for this type of fault as the disturbance becomes smaller in zones away from the fault.

For this fault it is expected that GBGF-Is in the local zone will leave the Normal Mode and use the Withstand Mode control for a short time before returning to the Normal Mode. The Withstand Mode can be based on the control and response as used by any viable control system. However, it is encouraged to remain in Grid forming behaviour unless current limiting is required.

For this fault condition, the phase angle of the local zone AC Grid can have very large phase angle changes that can be up to 90 degrees or larger. For this fault, all synchronous generators will produce reactive power and the large phase angle changes do not produce damaging mechanical transients.

b) The Feeder Closing Condition

This is when a feeder is closed on to the main AC Grid and a phase jump angle of up to 60 degrees can occur due to the control setting of the associated switchgear. This is a rare condition in a very small part of an AC Grid. The GBGF-Is only must remain in operation, without tripping, for this abnormal operating condition. This should ideally enable a system to provide a current near to its current limit rating.

c) The Control for a ROCOF Rate of 2 Hz / s

This is a specific GB Grid Code existing requirement and systems only have to remain in operation without tripping for the abnormal operating condition that should never occur.

3.2.4. GBGF-I Control System Model

Where applicable and appropriate, main features of GBGF-I model operating under Normal AC Grid operating conditions are suggested as follows:

a) Operate as a slowly changing real voltage source with an AC impedance.

b) Provide Active Phase Jump power with an initial response time defined by the AC supply impedance R_{ac} + L_{ac}.

c) Provide Active Inertia power with a response defined by the synthetic inertia, which is the same as or may be equivalent to the response of a GBGF-S generator that has real inertia with the same H value.

d) Provide Active Frequency Response Power that is produced by the control system's algorithms in response to a frequency change and is measured one second after the start of a ROCOF event.

e) Provide damping power. Damping factor can be greater than 1.

f) Control for the worst-case frequency transient: Control and rating validation of the associated energy store from the worst-case transient of 50 Hz to 52 Hz then to 47 Hz as defined in ECP.A.3.9.4. iv).

g) Provide a well-defined Transient Impedance Value "TIV" (Note: See [2] for more details).

A Normal Mode time domain simulation model, as shown on Figure 7, implements a basic time domain simulation model for a full three phase system. The three phase variables are the simulation model of the AC Grid and the DC variables are the software control system functions that have time varying signals.

This Normal Mode simulation model does not need to include the operation of the associated energy storage system because there are no control functions associated with an energy storage system directly connected to the DC bus of an inverter. If the energy storage system uses an extra inverter, then this model should be included.

The model also does not need to implement the current limit function of the GBGF-I as it is rated to not reach the current limit for the normal operating conditions of the GB AC Grid.

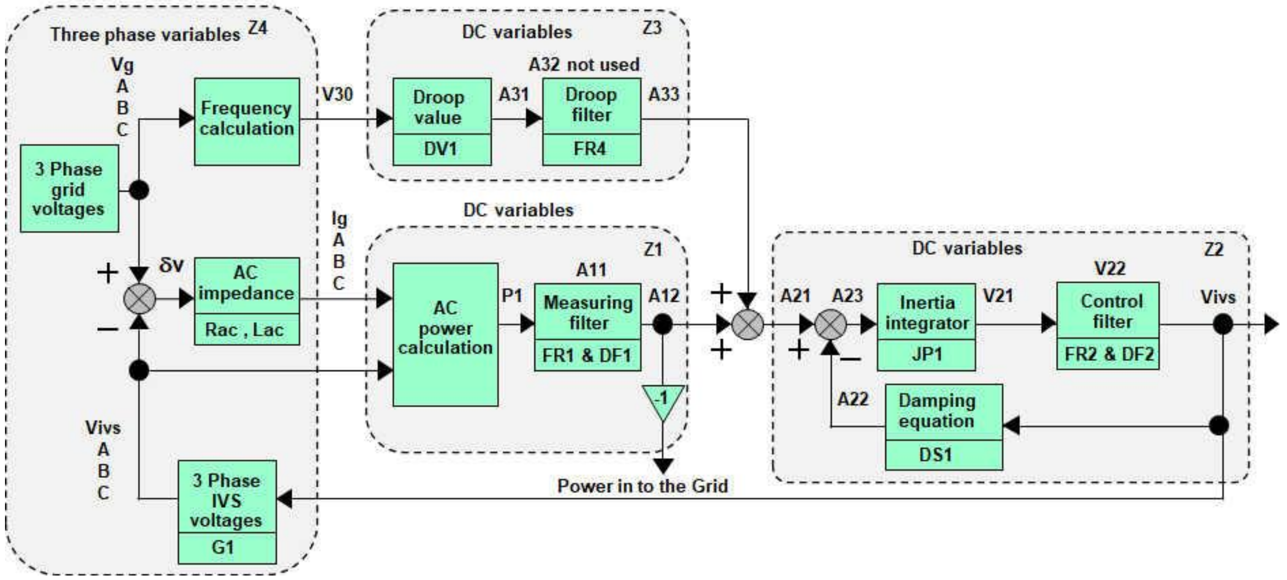


Figure 7: Typical Time Domain Simulation Model (Source: Enstore).

The main parts of the model shown in Figure 7 are:

- An integrating function to provide the systems appropriate inertia
- A damping function to allow the systems damping to be adjusted on site over a range of 0.2 to 2 pu
- Basic controls like a Droop control with a bandwidth limit of 5 Hz
- System's AC supply impedance with the Rac parameter that provides a low value of damping
- A closed loop response with a well damped resonant frequency that ensures that the inverter frequency tracks the AC Grid's frequency to keep the inverter synchronised to the AC Grid
- For a sudden change of the phase angle of the AC Grid a very fast AC current change will occur with a bandwidth of up to 1000 Hz but for all other changes the frequency and phase of the GBGF-I's IVS (Internal Voltage Source) only change slowly to produce Active Phase Jump power and give a very stable AC system

This is the model for the system operating in the Normal Mode.

There are several conditions that require a faster and non-linear action from a GBGF-I when the abnormal operating conditions occur. This is called the Withstand Mode. The operation of a specific GBGF-I for these abnormal operating conditions are:

a) A power overload that causes a phase jump angle greater than the set limits in the local zone and in the remote zone.

The GBGF-I provides the Phase Jump current limiting function for Phase Jump Angles that should not occur for normal operating conditions. This requires operation in the Withstand Mode for a very short time.

The worst case is for the withstand value of AC Grid's Phase Jump angle of 60 degrees at the rated AC voltage that can occur for closing a feeder on to the main AC Grid, this is to allow the associated AC circuit breakers to close with a phase difference of up to 60 degrees.

This is in the existing GB Grid Code and is a very rare condition in a very small part of an AC Grid.

b) A Power overload that causes a ROCOF rate greater than +/- 1 Hz/s. The GBGF-I provides the ROCOF rate limiting function for ROCOF rates up to +/- 2 Hz/s that should not occur for normal operating conditions. This requires operating in the Withstand Mode.
c) An AC grid short circuit fault. The GBGF-I provides the Fast Fault Current (FFC) function that can use the proven control methods of existing power converters. The GBGF-I can leave the Normal Mode and enter the Withstand Mode for a short time period before resuming operation in the Normal Mode.

A GBGF-I Withstand Mode model for this fault must include the following:

a) Control for large voltage dips and AC Grid short circuit faults. For this fault condition the phase angle of the local zone AC Grid can have very large phase angle changes that can be up to 90 degrees or larger.
b) During AC Grid short circuit faults, the GBGF-I will use Grid Fault Ride Through capability for a short time period, before resuming the Normal Mode operation. It is however encouraged to keep the Grid Forming behaviour during AC grid faults causing voltage dips beyond normal voltage ranges unless the current limiting is necessary to protect the Grid Forming Plant.

3.3. Suggestions for Further Grid Code Modifications

The key suggestions are captured by ESO in the Table 4 below following outcomes of the group discussions and data contributions in Subgroup 3 of the GBGF Best Practice Group.

Table 4: Key Suggestions as Captured by ESO after consulting with GBGF BPG Members.

Key Suggestions	Priority for Grid Code Change	Further Efforts during 2nd Round GC Mod.	Comments
Different operational modes should be clearly specified.	**Medium**	**Low**	To avoid confusion, Normal & Withstand Modes instead of “Linear” and “Non-Linear” Modes will be considered to reflect the operational conditions of GBGF Plants. Such definition and relevant Grid Code clauses will be reviewed and modified, where necessary, during the 2nd Grid Code Modification Working Group collaboration for GB Grid Forming.
The IBRs with pre-defined Grid Forming Mode should operate as long as possible to provide nature responses	**High**	**High**	Following two questions raised in group discussion: Question 1: When the voltage is below 0.9 p.u. yet the current limiter of the GFM inverter is not triggered, shall we force the inverter to fast inject the current (or equivalent active and reactive power)? Question 2: When the current limiter is triggered, e.g., the fault current of GFM inverter is clamped, shall we force the inverter to inject fully reactive current? The conclusions were made after comprehensive GBGF Best Practice Group discussions: The IBRs with pre-defined Grid Forming Mode should provide nature response as long as possible rather than transfer to Grid Following Mode for fast current injection. Relevant Grid Code requirements will be reviewed and updated, where necessary, during the 2nd Grid Code Modification Working Group collaboration for GB Grid Forming.

3.4. References

[1] ESO, Grid Code (GC) Issue 6 Revision 16, 5 January 2023.
URL: https://www.nationalgrideso.com/document/162271/download

[2] Enstore, “Basic specification of a GBGF inverter system – 002”, 9 August 2022.

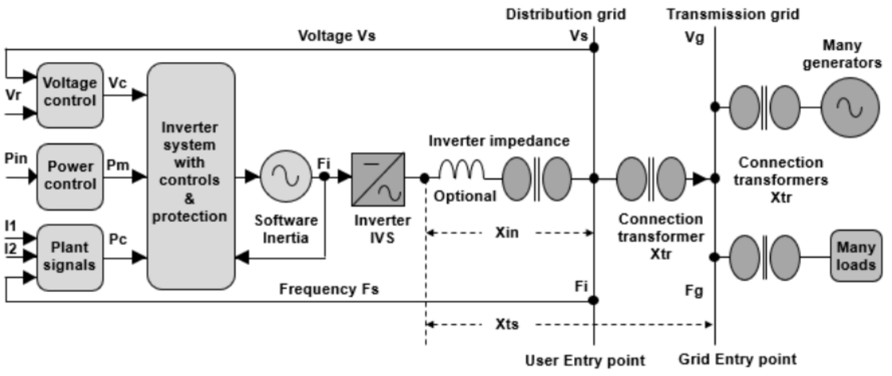
4. Key Definitions for GBGF-I

4.1. Introduction

A series of group discussions and major comments from members of GBGF Best Practice Group focus on the impedance definition of the equivalent Internal Voltage Source (IVS) of GBGF-I plants. The relevant Grid Code clauses are listed in the Table below. In addition, an example of the GBGF-I's impedance configuration is shown in Figure PC.A.5.8.1 as shown in the table below:

Relevant Grid Code Clauses [1]:

GD - Grid Forming Capability	Is (but not limited to) the capability a Power Generating Module, HVDC Converter (which could form part of an HVDC System), Generating Unit, Power Park Module, DC Converter, OTSDUW Plant and Apparatus, Electricity Storage Module, Dynamic Reactive Compensation Equipment or any Plant and Apparatus (including a smart load) whose supplied Active Power is directly proportional to the difference between the magnitude and phase of its **Internal Voltage Source** and the magnitude and phase of the voltage at the Grid Entry Point or User System Entry Point and the sine of the Load Angle. As a consequence, Plant and Apparatus which has a Grid Forming Capability has a frequency of rotation of the **Internal Voltage Source** which is the same as the System Frequency for normal operation, with only the Load Angle defining the relative position between the two. In the case of a GBGF-I, a Grid Forming Unit forming part of a GBGF-I shall be capable of sustaining a voltage at its terminals irrespective of the voltage at the Grid Entry Point or User System Entry Point for normal operating conditions. For GBGF-I, the control system, which determines the amplitude and phase of the **Internal Voltage Source**, shall have a response to the voltage and System Frequency at the Grid Entry Point or User System Entry Point) with a bandwidth that is less than a defined value as shown by the control system's NFP Plot. Exceptions to this requirement are only allowed during transients caused by System faults, voltage dips/surges and/or step or ramp changes in the phase angle which are large enough to cause damage to the Grid Forming Plant via excessive currents.
GD - Internal Voltage Source or IVS	For a GBGF-S, a real magnetic field, that rotates synchronously with the System Frequency under normal operating conditions, which as a consequence induces an internal voltage (which is often referred to as the Electro Motive Force (EMF)) in the stationary generator winding that has a real impedance. In a GBGF-I, switched power electronic devices are used to produce a voltage waveform, with harmonics, that has a fundamental rotational component called the **Internal Voltage Source** (IVS) that rotates synchronously with the System Frequency under normal operating conditions. For a GBGF-I there must be an impedance with only real physical values, between the **Internal Voltage Source** and the Grid Entry Point or User System Entry Point. For the avoidance of doubt, a virtual impedance, is not permitted in GBGF-I
ECC.6.3.19.3 (ii)	Each GBGF-I shall comprise an **Internal Voltage Source** and reactance. For the avoidance of doubt, the reactance between the Internal Voltage Source and Grid Entry Point or User System Entry Point (if Embedded) within the Grid Forming Plant can only be made by a combination of several physical discrete reactances. This could include the reactance of the Synchronous Generating Unit or Power Park Unit or HVDC System or Electricity Storage Unit or Dynamic Reactive Compensation Equipment and the electrical Plant and

	Apparatus connecting the Synchronous Generating Unit or Power Park Unit or HVDC System or Electricity Storage Unit (such as a transformer) to the Grid Entry Point or User System Entry Point (if Embedded).
ECC.6.3.19.3 (v)	Each GBGF-I shall be capable of: (b) Operating as a voltage source behind a real reactance. (d) include an Active Control Based Power part of the control system that can respond to changes in the Grid Forming Plant or external signals from the Total System available at the Grid Entry Point or User System Entry Point but with a bandwidth below 5 Hz to avoid AC System resonance problems.
PC.A.5.8.1	

Following those group discussions, this section provides background information and suggestions around the three topics as listed below:

a) To introduce background information of Virtual Impedance when introduced for GBGF-I, particularly its pros and cons.

b) To evaluate if Virtual Impedance can be introduced together with Real Impedance during normal operational conditions and transient conditions e.g. fault conditions and large disturbances – Does the ESO need to give clear definitions and requirements of virtual/real impedance (So-called **White Box**) or focus on functionality/performance as whole and inputs/outputs (So-called **Grey Box**).

c) To introduce background information of the Control 5Hz Bandwidth Limit.

4.2. Evaluation of Virtual Impedance

Generally, there are two types of Virtual Impedance, one is for damping under normal condition and the other is for the fault current limitation. There are different implementations for the Virtual Impedance, they have the same phasor characteristics R_v+jX_v but the high frequency (> 50Hz) response can be rather different. The easiest way to characterise the difference would be via frequency-domain spectrum plots.

The Virtual Impedance may change the network dynamics $R_v+jX_v+jX_L+sL$. R_v is helpful to damp the network mode (transient DC components decay faster), but X_v may shift the network mode to lower frequency and cause interaction between swing mode and network mode [2]. In this way, the applicable frequency range for the Virtual Impedance deserves close attention, as the virtual impedance may introduce negative effects at certain frequency range, which should be avoided. X_v may also change the fault-induced transient current profile: it may no longer be DC but be a negative sequence AC current.

The Virtual Impedance is closely related to fault level. As suggested in [3], the use of a variable Virtual Impedance instead of hard current limit during the fault may simplify the fault-level calculation and eliminate the need for hard mode switching between Grid Forming and Grid Following.

As a downside, the Virtual Impedance may reduce the grid strength and compromise part of the Grid Forming functionality and should be used with caution for weak grids. However, on the other hand, the Virtual Impedance may increase the adaptiveness of Grid Forming converters to a strong grid. As a result, the Virtual Impedance is a way to increase the robustness of Grid Forming control against a volatile grid environment, at the price of reduced performance (voltage and angle forming capability) at weak grids.

4.3. The Control 5Hz Bandwidth Limit

As suggested in [4], the limitation in the Grid Code ECC.6.3.19.3.(v).(d) of a 5 Hz bandwidth limit response for external signals is a very important requirement to make GBGF-I systems as stable as possible by isolating the response of the GBGF-I's IVS from fast changes in the AC Grid.

This is probably the main difference of GBGF-I systems when compared with the other Grid Forming inverter systems described in technical literature from other sources.

The AC Grid stability problems in existing systems were produced by a number of different software functions that Included:

(1) Fast acting Phase Locked Loop control functions, and similar control functions, responding to fast changes in the AC Grid's waveforms.
(2) Fast acting Current Control D and Q control loops, and similar control functions, responding to fast changes in the AC Grid's waveforms.
(3) Fast acting Synthetic Impedance control functions, and similar control functions, responding to fast changes in the AC Grid's waveforms.

The reasons for the 5 Hz limit are [5]:

a) To avoid the production of a continuous output of sub-harmonic frequencies from the GBGF-I in the range 5 to 50 Hz. This is because these sub-harmonics have been found to induce a mechanical resonance in other plant connected to the GB AC Grid, that can increase in amplitude to a damaging level when subjected to a continuous sub-harmonic excitation.

b) To avoid the system instability effects that have occurred in previous generations of inverter system that were using high bandwidth controls to control the output power in their normal operating mode. These high bandwidth controls have included:

- Phase Locked Loop "PLL" control
- D and Q current control loops
- Synthetic AC inverter control loops

There are fast acting control loops allowed within the control system of GBGF-I systems that includes the software damping function and the control of the associated plant.

These can cause low levels of current disturbances in the AC supply which is why the data in the Active Control Based Power GB Grid Code definition states: Active Control Based Power also includes Active Power components produced by the normal operation of a Grid Forming Plant that comply with the Engineering Recommendation P28 limits. These Active Power components do not have a 5 Hz limit on the bandwidth of the provided response.

For GBGF-I systems operating in the Withstand Mode, the GBGF-I systems IVS must change rapidly to avoid the GBGF-I systems from tripping. The Grid code allows any type of control software which is why the change to the Grid Code for ECC.6.3.19.3.(v).(d) has been proposed.

For the avoidance of doubt the following applies:

a) For a GBGF-I system operating in the Normal Mode, all control functions are allowed, including items (1), (2) and (3) in this Section 4.3 provided their control action conforms to the 5 Hz bandwidth limitation as listed in Grid Code ECC.6.3.19.3.(v).(d).

b) For a GBGF-I system operating in the Withstand Mode, all control functions are allowed, including items (1), (2) and (3) in this Section 4.3 with no limit on their bandwidth as listed in the proposed revision to Grid Code ECC.6.3.19.3.(v).(d).

4.4. Suggestions for Further Grid Code Modifications

The key suggestions are captured by ESO in Table 5 below following GB Grid Forming Best Practice Group discussions and data contributions from its Subgroup 1.

Table 5: Key Suggestions as Captured by ESO after consulting with GBGF BPG Members.

Key Suggestions	Priority for Grid Code Change	Further Efforts during 2nd Round GC Mod.	Comments
For the ESO's position, the Internal Voltage Source should be defined as the Grey Box so the clause, definition and figures as relevant to Virtual Impedance should be removed	**High**	**Low**	For the position of ESO, the equivalent Internal Voltage Source should be defined as a Grey Box rather than a White Box, where its functionality & performance as well as inputs/outputs should be clearly defined. Such a proposal of Grey Box has been widely supported by comprehensive external stakeholders during Best Practice Group discussions and individual stakeholder engagements for consultation purpose.
The Control Bandwidth Limits should be clearly defined during Normal Mode* for GBGF-I Plants	**Medium**	**Medium**	A clear and updated definition for a "Control 5 Hz Bandwidth Limit" will be further developed during the 2nd Grid Code Modification Working Group collaboration for GB Grid Forming. According to such definition as proposed, there may be other changes to the existing Grid Code that need to be proposed and agreed to finalise the 5 Hz limit during the 2nd Grid Code Modification Working Group collaboration for GB Grid Forming.

Note*: Background Information for the Normal Mode of GBGF-I, please see Chapter 3.

4.5. References

[1] ESO, Grid Code (GC) Issue 6 Revision 16, 5 January 2023.
URL: https://www.nationalgrideso.com/document/162271/download

[2] Y. Gu, N. Bottrell and T. C. Green, "Reduced-Order Models for Representing Converters in Power System Studies," in IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 3644-3654, April 2018.

[3] Qoria, Taoufik; Wu, Heng; Wang, Xiongfei, Colak, Ilknur (2022): Variable Virtual Impedance-based Overcurrent Protection For Grid-forming Inverters: Small-Signal, Large-Signal Analysis and Improvement. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.19565749.v1

[4] Enstore, "Final version of Proposed Grid Code Changes – 002F", 17 March 2023.

[5] Enstore, "Basic specification of a GBGF inverter system - 002", 9 August 2022.

5. Compliance Testing for GB Grid Forming Plant

5.1. Introduction

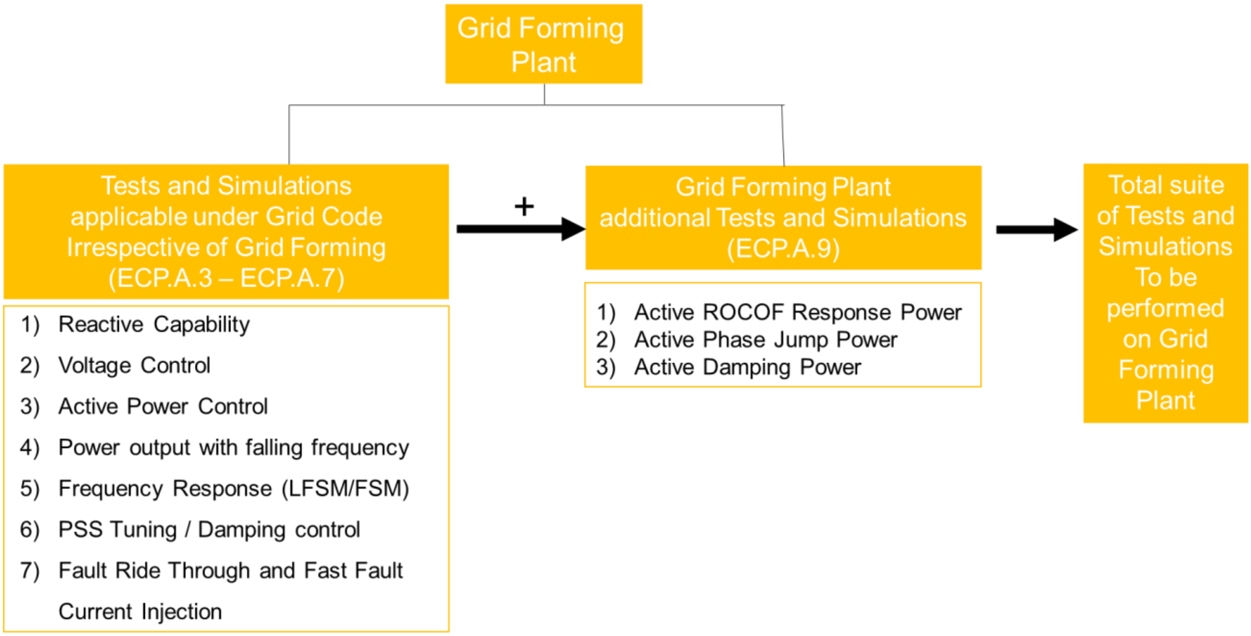


Figure 8: Typical Suite of Tests for Generic GB Grid Forming Plant.

Grid Forming Plants, as defined as GBGF-S or GBGF-I in Grid Code, can take many forms and can be a mixture of any of the technologies available as defined in the Grid Code. The list below indicates some typical Grid Forming technologies which are available, but this list is not exhaustive.

- Synchronous Condensers / Compensators with and without flywheels
- Synchronous Generators
- Grid Forming Converter storage systems
- Grid Forming Synchronous storage systems
- Grid Forming STATCOM Systems with an energy storage component
- Smart loads including Electric Vehicles (V2G)

It is also possible to mix the technologies to provide the overall Grid Forming package. It should be noted that, as part of this guidance, it is important that the provider tests compliance of each Grid Forming Plant type being proposed. In addition, at ESO's discretion, the Provider may need to test a combination of each technology at a single location to confirm service compliance and performance.

Generic compliance tests that all types of Grid Forming Plant are required to demonstrate are illustrated in Figure 8, the Scope of Work (SoW) of Generic Tests for Compliance Purpose are listed as follows [1]:

- Reactive Capability (including HV operation across voltage range)
- Voltage Control
- Active Power Control
- Power output with falling frequency
- Frequency Response (LFSM/FSM)
- PSS Tuning / Damping control
- Fault Ride Through and Fast Fault Current Injection

As suggested in Figure 8, the SoW of additional tests and simulations for the Grid Forming Plant are listed as follows

- Active ROCOF Response Power for GBGF-I
- Active Phase Jump Power for GBGF-I
- Active Damping Power for GBGF-I

Three sections, from Section 5.2 to Section 5.4, focus on all the specific additional tests and simulations for GBGF Plants with the key outcomes:

- Testing examples of Active ROCOF Response Power under extreme system frequencies as well as over the full system frequency range
- Testing examples of Active Phase Jump Power under normal operation
- Testing examples of Active Damping Power
- Discussion on Phase Jump Angle Withstand Value for Active Phase Jump Power under extreme conditions
- Discussion on the test for Active Phase Jump Power during a faulted condition

Following the discussions on the topics below, some potential grid code changes for relevant parts are suggested in Section 5.5.

5.2. Active ROCOF Response Power for GBGF-I

Relevant Grid Code Clauses [2]:

GD - Active ROCOF Response Power	The Active Inertia Power developed from a Grid Forming Plant plus the Active Frequency Response Power that can be supplied by a Grid Forming Plant when subject to a rate of change of the System Frequency.
GD - Active Inertia Power	The injection or absorption of Active Power by a Grid Forming Plant to or from the Total System during a System Frequency change. The transient injection or absorption of Active Power from a Grid Forming Plant to the Total System as a result of the ROCOF value at the Grid Entry Point or User System Entry Point. This requires a sufficient energy storage capacity of the Grid Forming Plant to meet the Grid Forming Capability requirements specified in ECC.6.3.19. For the avoidance of doubt, this includes the rotational inertial energy of the complete drive train of a Synchronous Generating Unit. Active Inertia Power is an inherent capability of a Grid Forming Plant to respond naturally, within less than 5ms, to changes in the System Frequency. For the avoidance of doubt, the Active Inertia Power has a slower frequency response compared with Active Phase Jump Power.
GD - Active Frequency Response Power	The injection or absorption of Active Power by a Grid Forming Plant to or from the Total System during a deviation of the System Frequency away from the Target Frequency. For a GBGF-I this is very similar to Primary Response but with a response time to achieve the declared service capability (which could be the Maximum Capacity or Registered Capacity) within 1 second. For GBGF-I this can rapidly inject or absorb Active Power in addition to the phase-based Active Inertia Power to provide a system with desirable NFP plot characteristics. Active Frequency Response Power can be produced by any viable control technology.

ECP.A.9.1.9.3	These tests are required to assess the Grid Forming Plant's withstand capabilities under extreme System Frequencies. (a) For Grid Forming Plant comprising a GBGF-I the frequency of the test network is increased from 50Hz to 52Hz at a rate of 2Hz/s with measurements of the Grid Forming Plant's Active ROCOF Response Power, System Frequency and time in (ms). (b) For a Grid Forming Plant comprising a GBGF-I the frequency of the test network is increased from 50Hz to 52Hz at a rate of 1Hz/s with measurements of the Grid Forming Plant's Active ROCOF Response Power, System Frequency and time in (ms). (c) For Grid Forming Plant comprising a GBGF-I the frequency of the test network is decreased from 50Hz to 47 Hz at a rate of 2Hz/s with measurements of the Grid Forming Plant's Active ROCOF Response Power, System Frequency and time in (ms). (d) For Grid Forming Plant comprising a GBGF-I the frequency of the test network is decreased from 50Hz to 47 Hz at a rate of 1Hz/s with measurements of the Grid Forming Plant's Active ROCOF Response Power, System Frequency and time in (ms).
ECP.A.9.1.9.4	This test is to demonstrate the Grid Forming Plant's ability to supply Active ROCOF Response Power over the full System Frequency range. (a) With the frequency of the test network set to 50Hz, the GBGF-I should be initially running at 75% Maximum Capacity or Registered Capacity, zero MVAr output and both Limited Frequency Sensitive Mode and Frequency Sensitive Mode disabled. (b) The frequency is then increased from 50Hz to 52Hz at a rate of 1Hz/s over a 2 second period. Allow conditions to stabilise for 5 seconds and then decrease the frequency from 52Hz to 47Hz at a rate of 1Hz/s over a 5 second period. Allow conditions to stabilise. (c) Record results of Active ROCOF Response Power, Reactive Power, voltage and frequency. (d) The test now needs to be re-run in the opposite direction. The same initial conditions should be applied as per ECP.A.9.1.9.4(a). (e) The frequency is then decreased from 50Hz to 47Hz at a rate of 1Hz/s over a 3 second period. Allow conditions to stabilise for 5 seconds and then increase the frequency from 47Hz to 52Hz at a rate of 1Hz/s over a 5 second period. Allow conditions to stabilise. (f) Record results of Active ROCOF Response Power, Reactive Power, voltage and frequency.

Two testing examples are presented below to illustrate the potential setup for compliance tests for ECP.A.9.1.9.3 and ECP.A.9.1.9.4. **It should be noted that the tests are from existing studies in [3][4], which are not designed for implementing the guideline as presented in the table above, so the steps and results are for illustration purpose only.** More details of the studies can be found in [3]-[5].

5.2.1. Simulation Test 1 – Active ROCOF Response Power under Extreme System Frequencies (ECP.A.9.1.9.3)

The testing examples for ECP.A.9.1.9.3 are presented below.

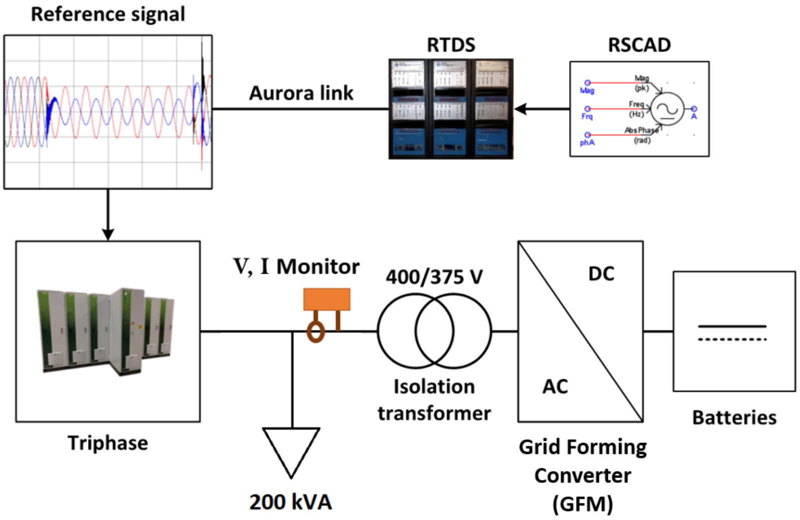


Figure 9: Test Setup and Network Configuration (Source: University of Strathclyde).

The example test setup is shown in Figure 9, where a grid emulator composed of a Triphase programmable bi-directional power converter rated at 540 kVA is used, along with a simulation model running on the real-time EMT simulation facility. Frequency profiles is defined in Real-Time EMT simulation facility, which is then used to control the Triphase output connected to the plant being tested for emulating the extreme frequency conditions. The fast response of the Triphase converter allows precise control of the terminal voltages to follow the defined frequency profiles.

In the first test, the GFM unit's power setpoint P_{set} is set as 100 kW exporting power and the inertia constant (H) is set as 4 s. The starting frequency of the grid is set as 50 Hz and a ROCOF of 2 Hz/s is applied for 1 s, followed by a ROCOF of -2 Hz/s for another 1 s to bring the frequency back to nominal value. The results for this test are shown in Figure 10, where it can be seen that, the event is initiated at around 4.3 s with a ROCOF of 2 Hz/s, and the frequency reaches 52 Hz at around 5.3 s. The GFM unit decreases its active power output in response to the positive ROCOF to provide emulated inertia support. Furthermore, disconnection of the GFM unit occurs at around 6.7 s can be observed, and it came back online at around 7 s.

It should be noted that the reason for ramping the frequency down right after reaching 52 Hz is due to the fact that the device under test has over-frequency protection with a threshold of 52 Hz, thus ramping down to avoid tripping.

In the second example test, a negative ROCOF of -2 Hz/s is applied for 1.5 s so that frequency of the system ends at 47 Hz. The inertia constant (H) value and other parameters of the system remained unchanged as the first example case. A ROCOF of -2 Hz/s for 1.5 s is applied in the test and results for the test are shown in Figure 11. As can be seen from the figure that a ROCOF of -2 Hz/s is applied at 5.4 s and as a result, active power supplied reaches to 209.58 kW from 101.69 kW, resulting in a power change of 107.89 kW. In this case, The GFM unit remains connected throughout the process.

It should be noted that the reason for ramping the frequency up right after reaching 47 Hz is due to the fact that the device under test has under-frequency protection with a threshold of 47 Hz, thus ramping up to avoid tripping.

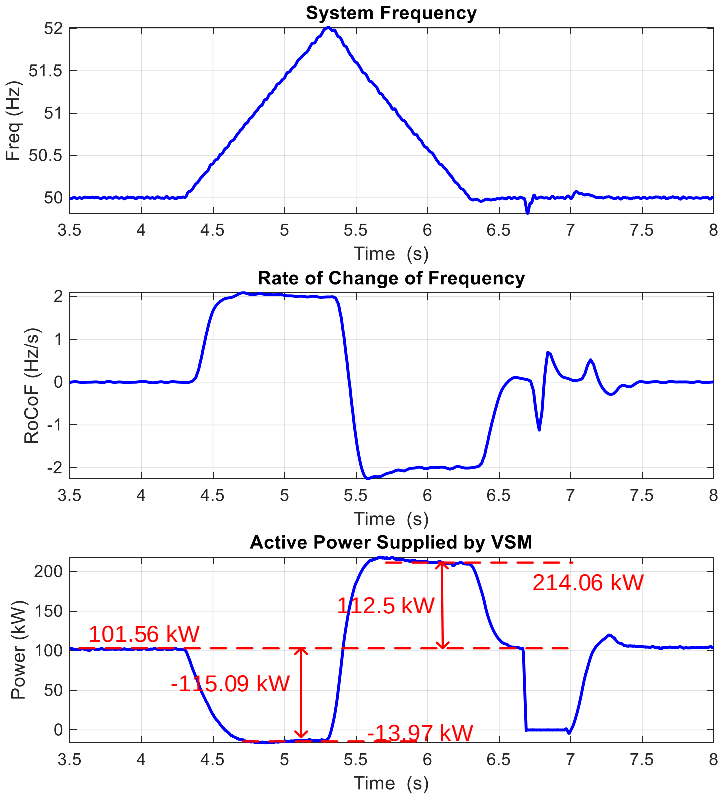


Figure 10. Results of Testing Example 1 (ECP.A.9.1.9.3 (i)) – Source: University of Strathclyde.

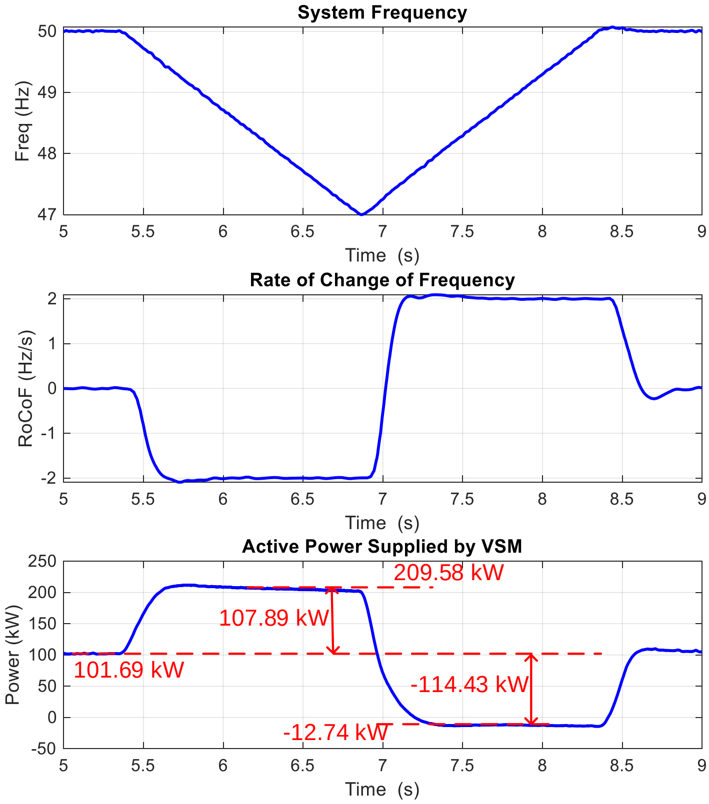


Figure 11. Results of Testing Example 2 (for ECP.A.9.1.9.3 (iii)) – Source: University of Strathclyde.

5.2.2. Simulation Test 2 – Active ROCOF Response Power over Full System Frequency Range (ECP.A.9.1.9.4)

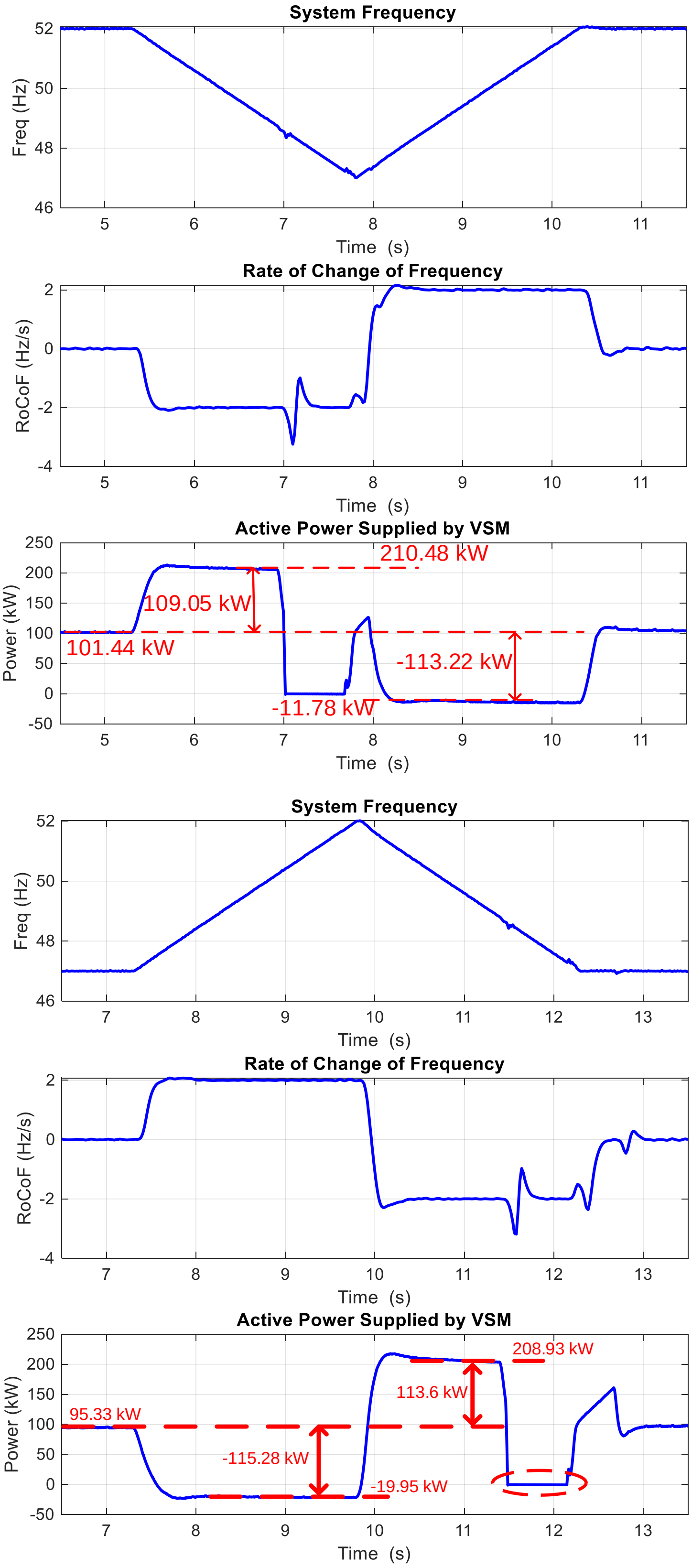


Figure 12: Example Results for ECP.A.9.1.9.4 (Source: University of Strathclyde).

The example tests for ECP.A.9.1.9.4 are presented in Figure 12 above.

In the first test, the Grid Forming Plant's power setpoint P_{set} is set as 100 kW exporting power (Note: in ECP.A.9.1.9.4, the setpoint is required to be 75% Maximum Capacity or Registered Capacity) and the inertia constant (H) is set as 4 s. In this test, the grid emulator is programmed to have a starting frequency of 52 Hz and is then ramped down at a ROCOF of -2Hz/s.

An inertial power of 109.05 kW is observed provided by the Grid Forming Plant due to the constant ROCOF. In the second part of this test, a positive ROCOF of 2 Hz/s is applied around 7.8 s, and a change of power of -113.22 kW can be observed. An unusual characteristic of the Grid Forming Plant can be observed in this test between 7 s to 7.8 s. When frequency decreases from 52 Hz and crosses the 49.5 Hz boundary (i.e. frequency drop is a bit more than 3.5 Hz), the Grid Forming Plant stops outputting power unexpectedly. However, it reconnects to the system when frequency reaches 47 Hz. It is considered that this could be due to an internal protection implemented as part of the control system.

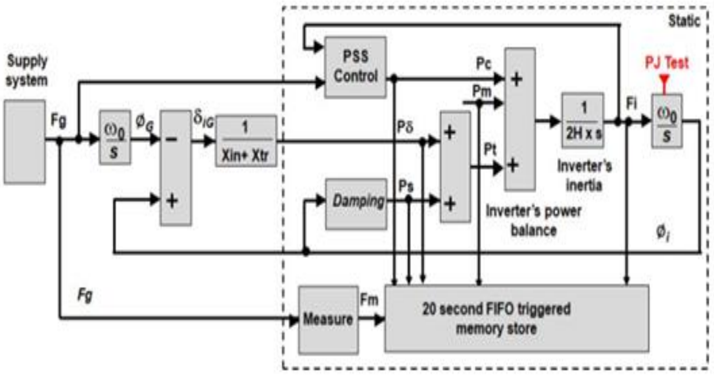
In this test, a frequency ramp of 2 Hz/s starting from 47 Hz (instead of 50 Hz) is applied at around 7.4 s until the frequency reaches 52 Hz. During the positive ROCOF, the GFM unit remains connected and provided an inertial power of -115.28 kW. However, during negative ROCOF of -2 Hz/s i.e. negative ramp from 52 Hz to 47 Hz, it can be observed that the tested GFM unit disconnects suddenly after a frequency drop of 3.5 Hz (i.e. frequency of 49.5 Hz and between 11.5 s and 12.1 s) and remains disconnected for few milliseconds. The GFM unit gets back online when the frequency stabilises at 47 Hz. A potential reason behind could be the same as the previous test described above.

5.3. Active Phase Jump Power for GBGF-I

Relevant Grid Code Clauses [2]:

GD - Active Phase Jump Power	The transient injection or absorption of Active Power from a Grid Forming Plant to the Total System as a result of changes in the phase angle between the Internal Voltage Source of the Grid Forming Plant and the Grid Entry Point or User System Entry Point. In the event of a disturbance or fault on the Total System, a Grid Forming Plant will instantaneously (within 5ms) inject or absorb Active Phase Jump Power to the Total System as a result of the phase angle change. For GBGF-I as a minimum value this is up to the Phase Jump Angle Limit Power. Active Phase Jump Power is an inherent capability of a Grid Forming Plant that starts to respond naturally, within less than 5 ms and can have frequency components of over 1000 Hz.
GD – Phase Jump Angle Limit	The maximum Phase Jump Angle when applied to a GBGF-I which will result in a linear controlled response without activating current limiting functions. This is specified for a System angle near to zero which will be considered to be the normal operating angle under steady state conditions
GD – Phase Jump Angle Withstand	The maximum Phase Jump Angle change when applied to a GBGF-I which will result in the GBGF-I remaining in stable operation with current limiting functions activated. This is specified for a System angle near to zero which will be considered to be the normal operating angle under steady state conditions.
ECP.A.9.1.9.5	This test is to demonstrate the Grid Forming Plant's ability to supply Active Phase Jump Power under normal operation. (a) With the frequency of the test network set to 50Hz, the GBGF-I should be initially running at Maximum Capacity or Registered Capacity or at its

	agreed deloaded point, zero MVAr output and all control actions (e.g. Limited Frequency Sensitive Mode, Frequency Sensitive Mode and voltage control) disabled. (b) Apply a positive phase jump of up to the Phase Jump Angle Limit at the Grid Entry Point or User System Entry Point (if Embedded). (c) This test can then be repeated by injecting the same angle into the Grid Forming Plant's control system (as indicatively shown in Figure ECP.A.9.1.9.5). This specific test can be repeated on site as required for a routine performance evaluation test. It should be noted that Figure ECP.A.9.1.9.5 is a simplified representation. Each Grid Forming Plant Owner can use their own design, that may be very different to Figure ECP.A.9.1.9.5 but should contain all relevant functions that can include test points and other equivalent data and documentation. Any additional signals, measurements, parameters and tests shall be agreed between the Grid Forming Plant Owner and The Company. (d) Repeat tests (b) and (c) with a negative injection up to the Phase Jump Angle Limit. (e) Record traces of Active Power, Reactive Power, voltage, current and frequency for a period of 10 seconds after the step change in phase has been applied. As part of these tests, the corresponding Active Power change resulting from a phase shift will be a function of the local reactance and the location of where the phase shift is applied in addition to any additional upstream impedance between the GBGF-I and phase step location.
ECP.A.9.1.9.6	This test is to demonstrate the Grid Forming Plant's ability to supply Active Phase Jump Power under extreme conditions. Where it is not possible to undertake this test as part of a type test, The Company will accept demonstration through a combination of simulation studies as required under ECP.A.3.9.4(vi) and online monitoring as required under ECC.6.6.1.9. (a) With the frequency of the test network set to 50Hz, the Grid Forming Plant should be initially running at its Minimum Stable Operating Level or Minimum Stable Generation, zero MVAr output and all control actions (e.g., Limited Frequency Sensitive Mode, Frequency Sensitive Mode and voltage control) disabled. (b) Apply a phase jump of 60 degrees at the connection point of the GBGF-I or into the Grid Forming Plant's control system as shown in Figure ECP.A.9.1.9.5. (c) Record traces of Active Power, Reactive Power, voltage, current and frequency for a period of 10 seconds after the step change in phase has been applied. (d) Repeat steps (a), (b) and (c) of ECP.A.9.1.9.6 but on this occasion apply a phase jump equivalent to the positive Phase Jump Angle Limit at the Grid.
ECP.A.9.1.9.7	This test is to demonstrate the GBGF-Is ability to supply Active Phase Jump Power, Fault Ride Through and GBGF Fast Fault Current Injection during a faulted condition. Where it is not possible to undertake this test as part of a type test, The Company will accept demonstration through a combination of simulation studies as required under ECP.A.3.9.4(vii) and online monitoring as required under CC.6.6 and ECC.6.6.1.9. (a) With the frequency set to 50Hz, the Grid Forming Plant should be initially running at its Maximum Capacity or Registered Capacity or at an alternative loading point as agreed with The Company, zero MVAr output and all control actions (e.g., Limited Frequency Sensitive Mode, Frequency Sensitive Mode and voltage control) disabled.

<table>
<tr><td></td><td>(b) Apply a solid three phase short circuit fault at the connection point in the test network forming part of the type test for 140ms or alternatively the equivalent of a zero retained voltage for 140ms.
(c) Record traces of Active Power, Reactive Power, voltage, current and frequency for a period of 10 seconds after the fault has been applied.
(d) Repeat steps (a) to (c) but on this occasion with fault ride through, GBGF Fast Fault Current Injection Limited Frequency Sensitive Mode and voltage control switched into service.
(e) Record traces of Active Power, Reactive Power, voltage, current and frequency for a period of 10 seconds after the step change in phase has been applied and confirm correct operation.</td></tr>
<tr><td>Figure ECP.A.9.1.9.5</td><td>
</td></tr>
<tr><td>Table PC.A.5.8.2</td><td>
<table>
<tr><td>Quantity</td><td>Units</td><td>Range (where Applicable</td><td>User Defined Parameter</td></tr>
<tr><td>Phase Jump Angle Limit</td><td>Degrees</td><td></td><td>**5 degrees recommended**</td></tr>
<tr><td>Phase Jump Angle Withstand</td><td>Degrees</td><td></td><td>**60 degrees specified**</td></tr>
</table>
</td></tr>
</table>

5.3.1. Simulation Test 1 – Active Phase Jump Power under Normal Operation (ECP.A.9.1.9.5)

A testing example for GBGF-I is illustrated in Figure 13 [6]. The following actions occur for an AC Grid phase angle change:

- The inverter's output voltage does not change its magnitude, frequency or phase
- The AC supply current occurs due to the change in the phase angle of the AC supply
- The rate of rise of the current is defined by the L_{ac}
- The current amplitude is given by 2 x sin (phase angle change / 2) / AC impedance in pu
- This produces a current transient as shown on Figure 13

The magnitude of the phase angle is the rated value of the system's Phase Jump Angle Limit. The test should be carried out for +ve and -ve phase angle changes that are applied with a phase change time of 1 and 20 milliseconds to the AC Grid'. This is a set of 4 tests.

The decay time of the current's main waveform is defined by the system's resonant frequency. The essential feature is that the phase angle of the GBGF-I's IVS does not change at the start of the transient.

This can be recorded by either an output signal of the GBGF-I's IVS phase shift signal or by a measurement of the inverter's real output voltage via a second order low pass filter.

This test should be repeated using the Phase Test Signal shown on Figure 14 to validate that this test signal produces identical results. This validates that the Phase Test Signal can be used on site for commissioning and routine testing. The Phase Test Signal must be provided by the supplier of a GBGF-I.

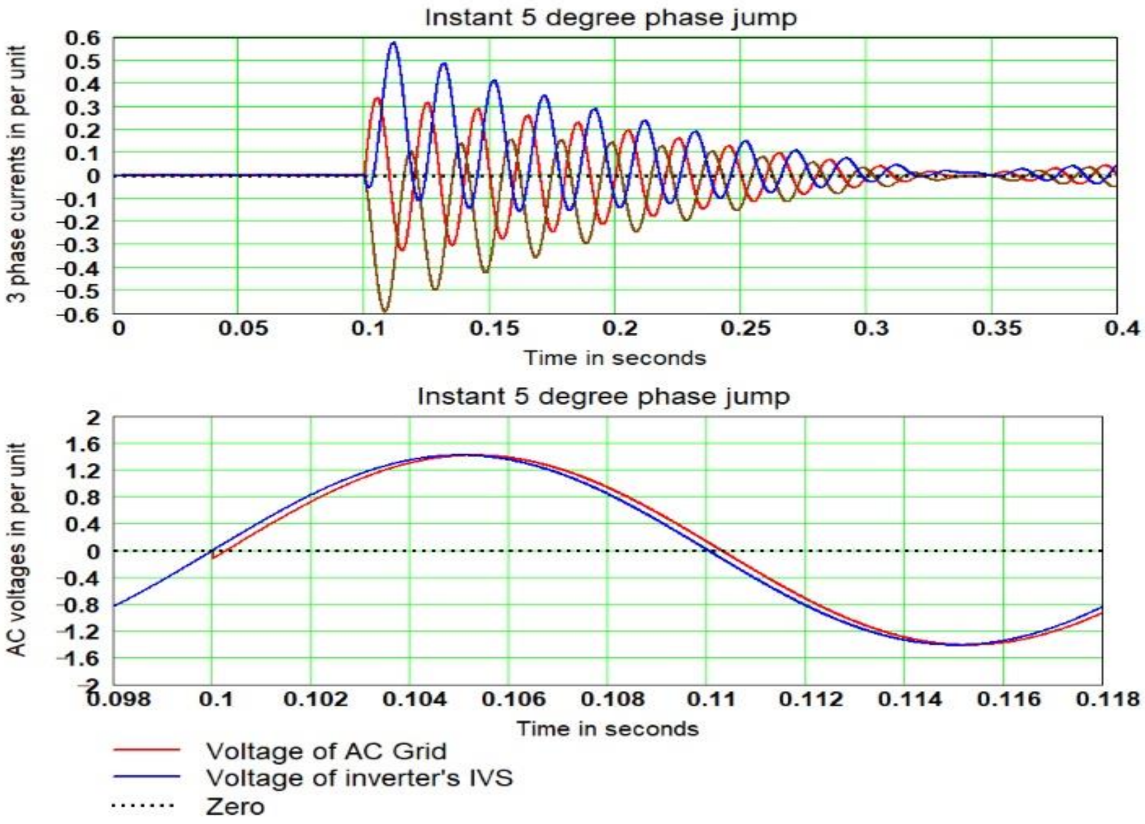


Figure 13: Phase Jump Current Transient Test (Source: Enstore).

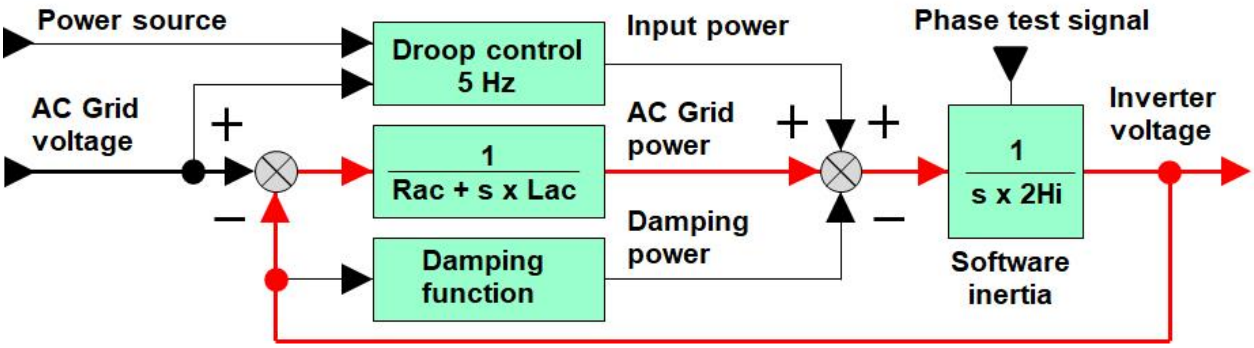


Figure 14: A typical Normal Mode System for GBGF Plant (Source: Enstore).

5.3.2. Simulation Test 2 – Active Phase Jump Power under Extreme Conditions (ECP.A.9.1.9.6)

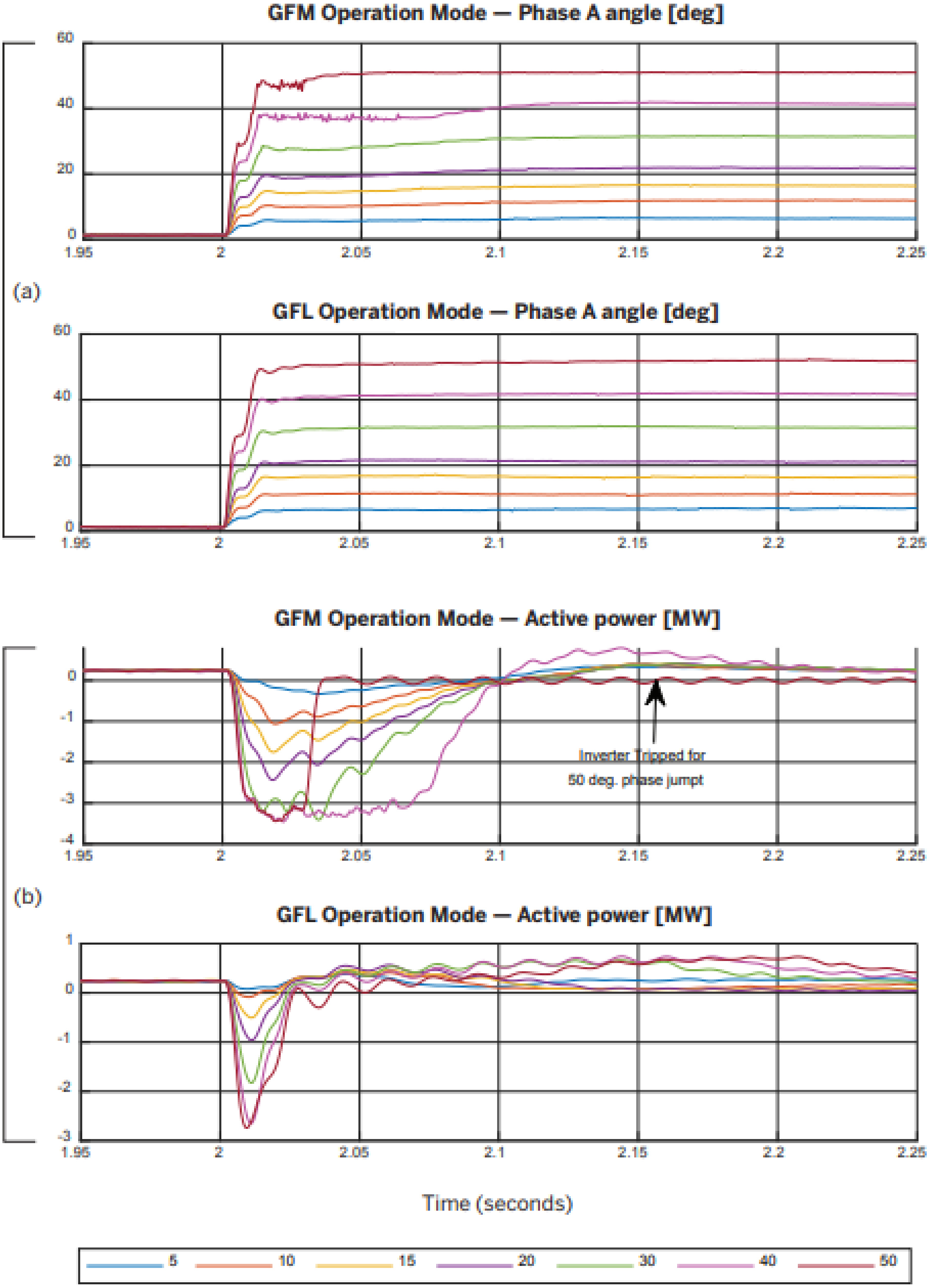


Figure 15: Active Power Responses of an Inverter to Phase Jump in Its Terminal Voltage for GFM and GFL Operation Mode (Source: NREL).

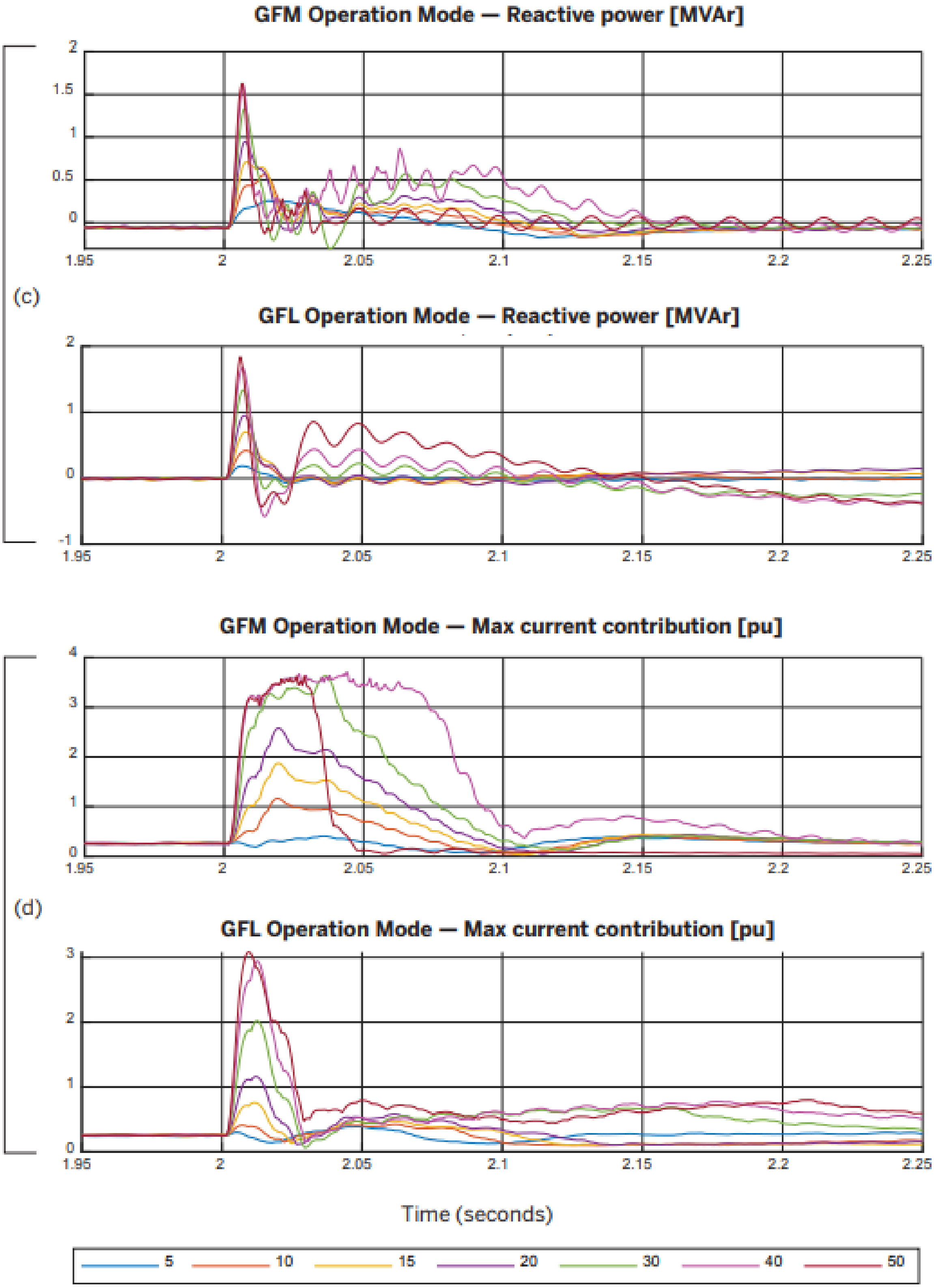


Figure 16: Reactive Power and Max Current Contribution Responses of an Inverter to Phase Jump in Its Terminal Voltage for GFM and GFL Operation Mode (Source: NREL).

The Phase Angle Jump is widely regarded as a very important issue when addressing the Phase Angle Ride Through (PART) capability of IBR as a large phase angle jump may cause overcurrent of inverters and hence the disconnection of these inverters from the Power Grid.

The maximum Phase Angle Change for withstand purposes is very important for defining the reasonable PART capability. Although higher values of phase jump angle have been observed from research papers (e.g. 79.2 degrees as indicated in [7], the maximum phase jump angle of 60 degrees has been recommended from the IEEE Standard [8].

During the Best Practice Group discussion, a phase jump scenario of 60 degrees has been suggested [9]: Control for the withstand value of AC Grid's Phase Jump angle of 60 degrees at the rated AC voltage that can occur for closing a feeder on to the main AC Grid, this is to allow the associated AC circuit breakers to close with up to a phase difference of up to 60 degrees. This is in the existing GB Grid Code but is a very rare condition in a very small part of the AC Grid as discussed in the Best Practice Group discussions.

Figure 15 and Figure 16 show the study results of response of the 2.3 MVA hardware inverter in GFL and GFM modes during phase jumps of magnitudes ranging from 5 to 50 degrees with the key findings [10]:

a) During the phase jump angle range of 5-50 degrees, the GFM-based inverter was able to ride through all phase-jump tests.

b) The GFM-based inverter responded more aggressively to phase jump events than GFL-based inverters due to different typical characteristics of GFL mode (as a controlled current source) and GFM mode (as an independent voltage source).

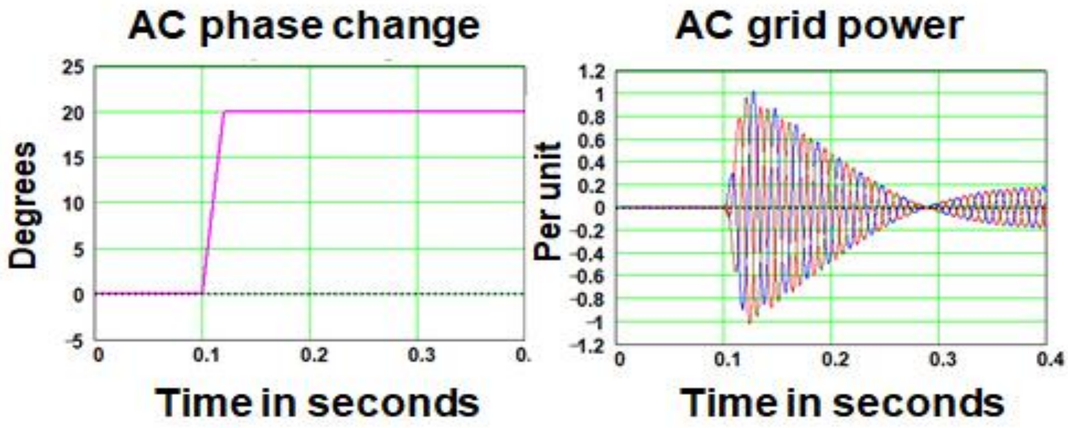


Figure 17: Typical AC Phase Jump Angle Current (Source: Enstore).

As a result, as suggested in [10], this may be a challenging requirement for these IBRs to ride through a phase jump event with 60 degrees of phase angle change. In order to achieve compliance for such a large phase jump of up to 60 degrees, increasing advanced grid-support capabilities are required to be developed and commercially employed within the GB system in line with compliance requirements.

Following a comprehensive literature review of the GBGF Best Practice Group there are a large number of publications on the testing of the impacts of phase angle jump on the system dynamics and PART capability. There are however no sufficient research studies on quantification of the reasonable values of Phase Jump Angle Withstand that need be considered in the rolling out of GBGF-Is. The Phase Jump of IBRs is a complex issue as it depends on many factors including the inverter control system parameters, inverter loading conditions prior to the fault and grid impedance/fault impedance at the location.

As the results show, further efforts will be needed during future Grid Code modification workgroups to work on identification of the reasonable Phase Jump Angle Withstand for rolling out GBGF-Is across GB. A reasonable phase jump change event with 20 degrees is illustrated in Figure 17 [9].

5.3.3. Simulation Test 3 – Active Phase Jump Active Power during a faulted condition for GBGF-I (ECP.A.9.1.9.7)

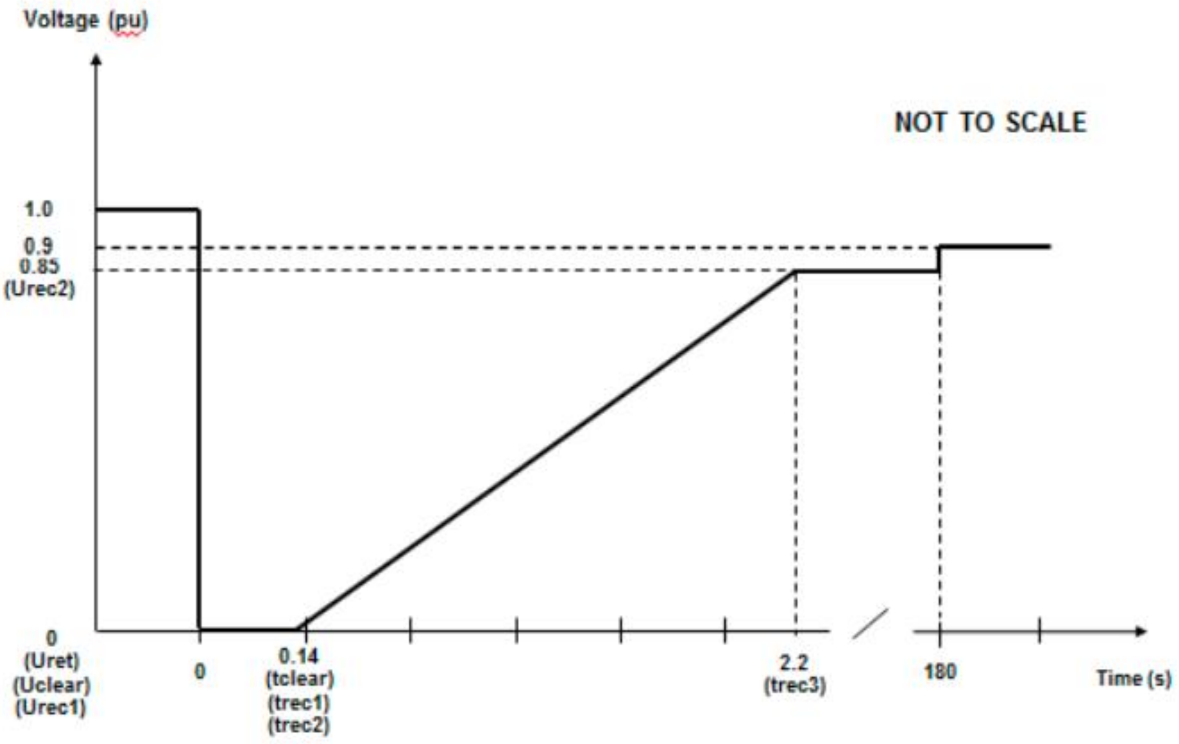


Figure 18: Fault Ride Through Curve for IBRs at Interface Point at or above 110kV.

According to outcomes of group discussion: The 3Ph-to-Earth symmetrical fault within GB system at 110kV or above is generally considered as the most severe scenario for faulted conditions.

In this way, for an example, for the IBRs as connected at the Interface Point at or above 110kV, the voltage against time curve and parameters can be illustrated in Figure 18 according to the Grid Code.

For such a scenario, as shown in (1) the output active power is independent from such phase angle changes when the voltage dip can reach to 0.0 pu at the Interface Point (**V_{IP}**=0) or Connection Point during such a fault condition as the initial power response is dominated by

$$P_\delta = \frac{EV_{IP}}{X} sin\delta \qquad (1)$$

In this way, the Fault Ride Through can cover such scenarios and further Phase Angle Ride Through is not needed. For the avoidance of doubt, the scope of work for the tests of active phase jump power under extreme conditions will not include faulted conditions as discussed.

5.4. Active Damping Power for GBGF-I

Relevant Grid Code Clauses [2]:

GD - Active Damping Power	The Active Power naturally injected or absorbed by a Grid Forming Plant to reduce Active Power oscillations in the Total System. More specifically, Active Damping Power is the damped response of a Grid Forming Plant to an oscillation between the voltage at the Grid Entry Point or User System Entry Point and the voltage of the Internal Voltage Source of the Grid Forming Plant. For the avoidance of doubt, Active Damping Power is an inherent capability of a Grid Forming Plant that starts to respond naturally, within less than 5ms to low frequency oscillations in the System Frequency.
ECP.A.9.1.9.8	The final test required is to demonstrate the GBGF-I is capable of contributing to Active Damping Power. The Grid Forming Plant Owner should configure their Grid Forming Plant in form or equivalent (as agreed with The Company) as shown in Figure ECP.A.3.9.6(a) or Figure ECP.A.3.9.6(b) as applicable. Each Grid Forming Plant Owner can use their own design, that may be very different to Figures ECP.A.3.9.6(a) or ECP.A.3.9.6 (b) but should contain all relevant functions. As part of this test, the Grid Forming Plant Owner is required to inject a signal into the Grid Forming Plant controller. The results supplied need to verify the following criteria:- (a) Inject a Test Signal into the Grid Forming Plant controller to demonstrate the Active Control Based Power output is supplied below the 5Hz bandwidth limit An acceptable performance will be judged where the overshoot or decay matches the Damping Factor declared by the Grid Forming Plant Owner as submitted in PC.A.5.8.1 in addition to assessment against the requirements of CC.A.6.2.6.1 or ECC.A.6.2.6.1 or CC.A.7.2.2.5 or ECC.A.7.2.5.2 as applicable.

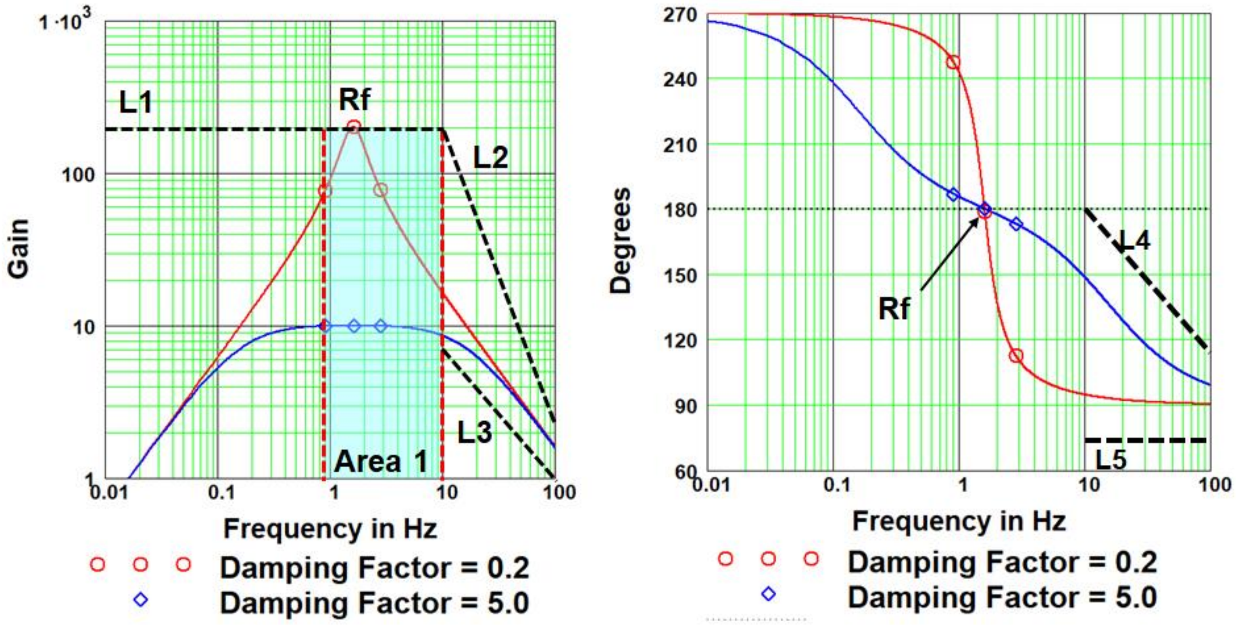


Figure 19: The NFP Plot Test without Control Functions (Source: Enstore).

5.4.1. Testing Example 1

A testing example based on NFP is introduced in [6]:

a) This is to apply an appropriate test signal with an amplitude of 0.01 pu RMS with a frequency of 1 Hz together with the system's AC Grid's voltage with an amplitude of 1.0 pu.
b) The measured current amplitude and phase at the 1 Hz test frequency gives one point on the NFP plot and the test signal is applied to the three phases of the AC Grid's voltage.
c) This test is repeated with 5 points in each frequency band from 0.01 Hz to 20 Hz which typically provides 16 data points that can be compared with the system's simulated NFP plot shown on Figure 19.
d) This frequency domain test is limited to 20 Hz due to cross modulation effects with the 50 Hz main grid frequency.
e) The Figure 19 is for a NFP test produced in the frequency domain that can plot the NFP plot for test frequencies above 20 Hz.
f) This test is initially done with all the added control features turned off as shown on Figure 14 and with the damping software set to give a Damping Factor of 0.2.
g) This validates the system's resonant frequency and damping software for one set of the system's parameters.
h) The test is repeated with all the added control features enable to give the systems full NFP plot.
i) The test is repeated with the input at the system's resonant frequency with the system's damping set to give a Damping Factor of 5.
j) The results of these test data points can be compared with the system's simulated NFP plot shown on Figure 19 including complying with the five limit lines and Area1.

5.4.2. Testing Example 2

Another example based on NFP is introduced in [3] and [5]:

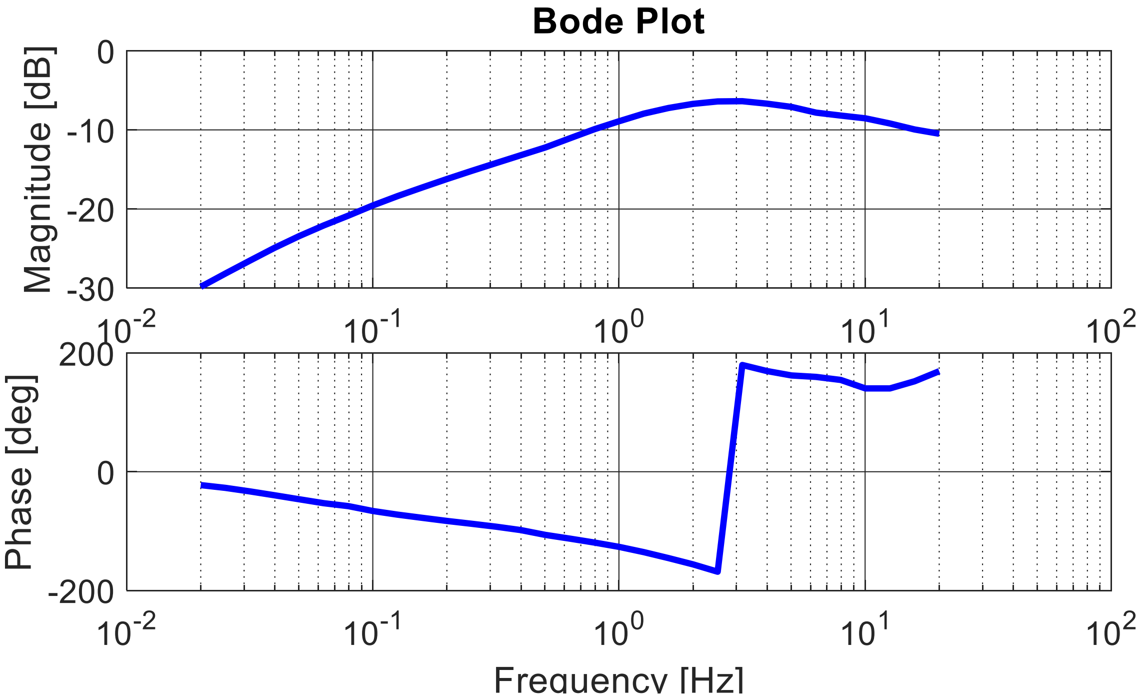


Figure 20: Bode Plot for Frequency Sweep Test (Source: University of Strathclyde).

In this set of tests, frequency sweep using the NFP approach with Real-Time EMT simulation facility, controlling the Triphase as a voltage source is performed as shown in Figure 9. The test is performed as follows:

a) The 3-phase voltage source (grid emulator) is programmed in the Real-Time EMT simulation facility with its frequency defined in Section 2:

$$f = f_0 + \Delta f\, cos(2\pi f_{mod}) \tag{2}$$

Where:

- $f_0 = 50\, Hz$
- $\Delta f = 0.5\, Hz$, the selection value of perturbance amplitude depends on the expected peak response around the resonant frequency (typically 1–3 Hz)
- f_{mod}: Frequency of the modulation in Hz (from 0.02 Hz to 20 Hz in these tests)
- Voltage magnitude will be maintained at nominal at all times

b) At any given value of f_{mod} the GFM unit's output is captured the same way as for all the other tests (e.g. frequency, ROCOF, voltage, current and power supplied by the GFM unit). The only difference is that during the NFP test, the collection of data during a steady state condition required a sufficiently long time, i.e. at least one (preferably two) cycles of the modulation frequency. The modulation frequency is changed from 0.02 Hz to 20 Hz. To achieve a reasonably accurate representation of the characteristic, approximately 10 tests have been performed per decade, i.e. 30 tests within 3 decades (0.2, 2 and 20 Hz).

c) The instantaneous power for each of the recorded steady state conditions is analysed using a Fourier Transform to determine the amplitude and phase of the Grid Forming Plant's frequency response.

Figure 20 presents the "Bode Plot" that has been achieved through the above mentioned NFP test and Fourier transform of the recoded results from the tested GFM unit.

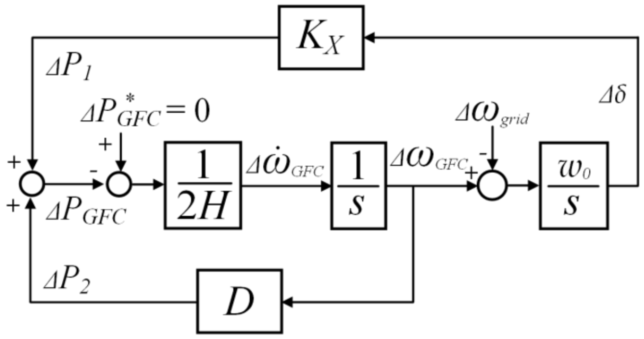


Figure 21: Block Representation of a Second Order Grid Forming Converter (Source: University of Strathclyde).

A general representation of a second order Grid Forming Plant with inertial control is shown in Figure 21, and the overall transfer function of the represented Grid Forming Plant's block diagram is shown in (3). The following relationship shown in (4) and (5) can be derived from the overall transfer function of the Grid Forming Converter as discussed in [5], where, ω_n and ζ can be calculated from the Bode Plot as shown in Figure 20. Subsequently, using (4) and (5), inertia constant, H and damping constant, D of the Grid Forming Plant can be determined through (6) and (7) respectively.

$$\frac{\Delta P_{GFC}(s)}{\Delta\omega_{grid}(s)} = \frac{-K_X s}{s^2 + \frac{D}{2H}s + \frac{K_X\omega_0}{2H}} \tag{3}$$

$$\omega_n = \sqrt{\frac{K_X\omega_0}{2H}} \tag{4}$$

$$\zeta = \frac{D}{4}\sqrt{\frac{2}{HK_X\omega_0}} \tag{5}$$

$$H = \frac{K_x\omega_0}{2\omega_n^2} \tag{6}$$

$$D = \frac{4\zeta}{\sqrt{\frac{2}{H\omega_0 K_X}}} \tag{7}$$

a) Approach 1: Peak Response

To calculate the value of H and D through (4) and (5), firstly, the value of ω_n and ζ needs to be determined from Figure 20. Hence, the magnitude of the Bode plot has been zoomed in near the peak response and shown in Figure 22. Using $\omega_n = 2\pi f_n = 18.54\ \mathrm{rad}/s$ and $K_X = 8.33$, the estimated value of $H = 3.81\ s$. Similarly, using (5), the estimated value of $D = 183.58$, where, $\zeta = \frac{1}{2Q}$ and $Q = \frac{f_n}{f_2 - f_1}$.

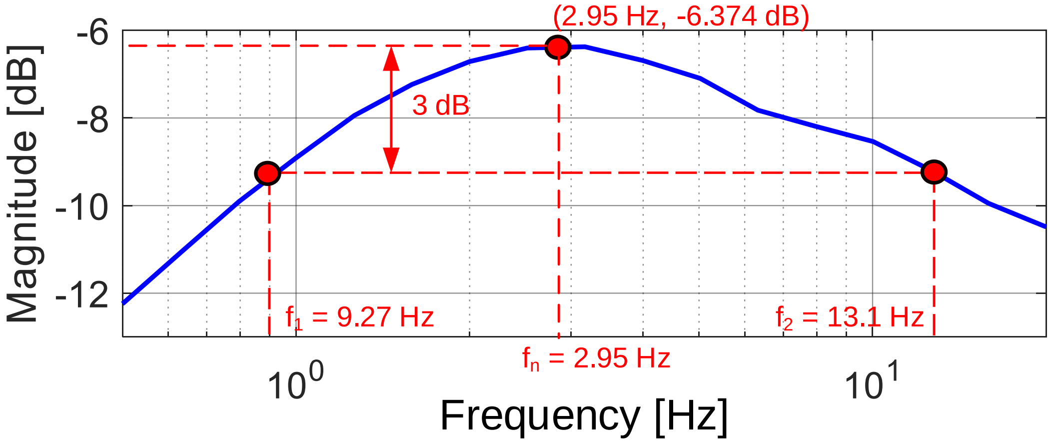


Figure 22: Magnitude in Bode Plot (Source: University of Strathclyde)

b) Approach 2: Curve Fitting Approach

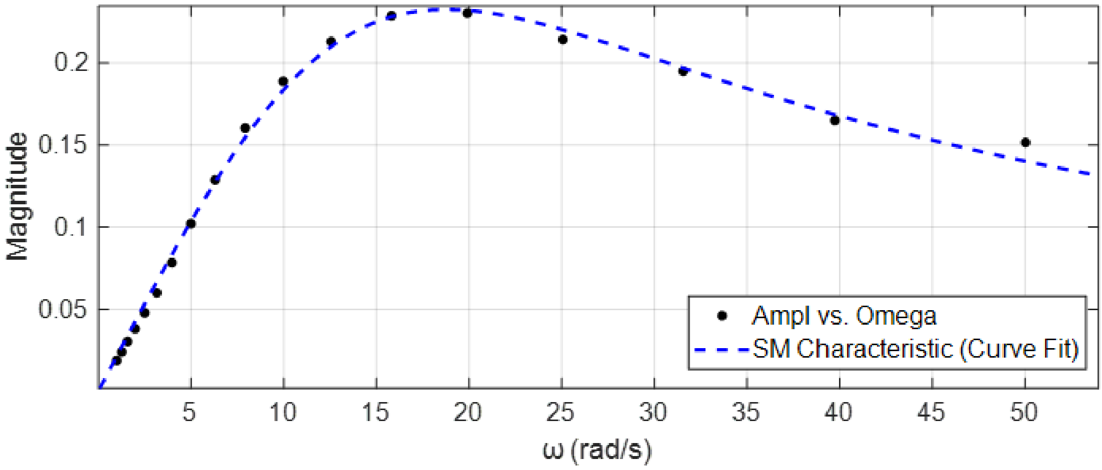


Figure 23: Estimating H and D through Amplitude Characteristic Curve Fitting (Source: University of Strathclyde).

The second approach of calculating H and D of the Grid Forming Plant is using a curve fitting method. In this approach, a curve fitting graph is plotted as presented in Figure 23, where the dynamic model of the Grid Forming Plant is utilised to obtain the frequency characteristics which is subsequently fitted into the (3) in order to obtain the unknown values of H and D. From Figure 23, the estimated values of H and D are 3.372 s and 218.9 respectively.

The actual and estimated values of H and D calculated using the two aforementioned approaches are shown in Table 6. The assumed values of H and D (provided by the manufacturer) for the Grid Forming Plant were 2 s and 256 respectively. **It should be noted that the errors presented in Table 6 do not indicate the effectiveness or accuracy of the presented methods, but the level of difference of the inertia response and damping from the Grid Forming Plant as compared with an equivalent synchronous generator with the same inertia and damping constant.**

Table 6: Estimation of H and D with Different Approaches (Source – University of Strathclyde).

Method		Actual H	Estimated H	Error H	Actual D	Estimated D	Error D
Frequency Sweep	Peak Response with $K_X = 8.33$	2 s	3.81 s	90.5%	256	183.58	-28.29%
	Peak Response with $K_X = 7.557$		3.45 s	72.5%		166.51	-34.96%
	Curve fitting		3.372 s	68.6%		218.89	-14.5%

5.5. Suggestions for Further Grid Code Modifications

The key suggestions are captured by ESO in Table 7 below following GB Grid Forming Best Practice Group discussions and data contributions from its Subgroup 4.

Table 7: Key Suggestions as Captured by ESO after consulting with GBGF BPG Members.

Key Suggestions	Priority for Grid Code Change	Further Efforts during 2nd Round GC Mod.	Comments
Phase Jump Angle Withstand of 60 degrees should be further evaluated for further roll-out of GB Grid Forming applications.	**High**	**High**	During 2nd Grid Code Modification Working Group collaboration for GB Grid Forming, further efforts are needed to identify the answers to key challenging questions as listed below: a) For Power Grid applications, how to determine the maximum voltage phase angle jump of inverters at different locations with different voltage levels? b) Are the maximum voltage phase angle jump of inverters the same for different applications? c) Is the maximum phase angle jump of 60 degrees too big or not sufficient?
ECP.A.3.9.4 vi) should make it clear that faulted conditions is not included within the range of extreme conditions for tests of Phase Angle Ride Through for Compliance Purpose.	**Medium**	**Medium**	During 2nd Grid Code Modification Working Group collaboration for GB Grid Forming, further efforts are needed to identify what would the reasonable most severe worse scenario under extreme conditions and relevant Phase Jump Angle Withstand accordingly.

5.6. References

[1] ESO Compliance Process,
URL: https://www.nationalgrideso.com/industry-information/connections/compliance-process.

[2] ESO, Grid Code (GC) Issue 6 Revision 16, 5 January 2023.
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[3] A. Khan, Q. Hong*, D. Liu, A. Egea Alvarez, A. Avras, A. Dysko, C. Booth, and D. Rostom, Experimental Assessment and Validation of Inertial Behaviour of Virtual Synchronous Machines, IET Renewable Power Generation, 2022. https://doi.org/10.1049/rpg2.12496.

[4] A. Dyśko, A. Egea, Q. Hong, A. Khan, P. Ernst, R. Singer, and A. Roscoe, Testing Characteristics of Grid Forming Converters Part III: Inertial Behaviour, 19th Wind Integration Workshop, 2020.

[5] ESO's NIA Project "Demonstration of Virtual Synchronous Machine Control of a Battery System", Ref. NIA_NGSO0026 (Complete), URL: https://smarter.energynetworks.org/projects/nia_ngso0026/.

[6] Enstore, "Basic specification of a GBGF inverter system - 002", 9 August 2022.

[7] X. Tian, G. Li, Y. Chi, W. Wang, H. Tang and X. Li, "Voltage phase angle jump characteristic of DFIGs in case of weak grid connection and grid fault," Journal of Modern Power Systems and Clean Energy, vol. 4, no. 2, pp. 256-264, April 2016, doi: 10.1007/s40565-015-0181-4.

[8] IEEE Standard 15471-2020 "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces".

[9] Enstore, "The Enstore guide to GB Grid Forming technology 002", 21 April 2022.

[10] ESIG, "Grid-Forming Technology in Energy System Integration", March 2022.
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