From. **Enstore.**

Date. **9 August 2022.**

To. **Dechao Kong, Terry Baldwin and Anthony Johnson at NGESO and any other persons.**

Data. **Basic specification of a GBGF inverter system – 002.**

Contents

0. Introduction.

This document contains data on the primary requirements for a GB Grid Forming inverter and related data.

1. Acronyms.

ESS	Energy storage system.	PWM	Pulse Width Modulation system.
FIFO	First In First Out data storage system.	pu	The value in the per unit rating method.
Fm	Frequency Measured from the AC Grid.	Rac	The resistance of the AC supply.
GBGF	GB Grid Forming technology.	Rf	Resonant frequency of a GBGF system.
GCP	Grid connection point.	RoCoF	Rate of Change of Frequency.
GFBPW	GB Grid Forming best practice workgroup.	RoCoF 1	RoCoF rate in the main AC Grid.
H	The NGESO definition of stored energy.	RoCoF 2	Higher RoCoF rate in a local zone of the Grid.
Hi	The per unit value of the software inertia.	SIC	Sensors and inverter control.
IVS	Internal voltage source.	Sm	Synchronous machine.
Lac	The inductance of the AC supply.	SPF	Stability Pathfinder part of the TSS.
NFP	Network frequency perturbation.	SQSS	Security and quality of supply standard.
NGESO	National Grid electricity system operator.	TIV	Transient Impedance value.
Pd	Phase Difference between two angles.	TSS	Transmission Stability Service.
Pp	Primary power source.	VSM	Virtual synchronous machine.
PLL	Phase Locked Loop or similar control.	Xin	Impedance of the inverter’s inductor.
PMR	Power Monitoring and Recording.	Xtr	Impedance of the AC transformer.
PMU	NGESO Phasor measurement unit.	s	The Laplace s domain operator.

2. The operating modes, rating and requirements for a GB Grid Forming inverter.

GBGF inverter has two operating Modes that will be defined in a future Grid Code update.

2.1. The GBGF Normal Mode.

For this mode a GBGF inverter is operating in conditions that are below the **Peak Current Rating** where all the GBGF Grid Code requirements apply including the 5 Hz bandwidth limit.

The GBGF inverter only produced a balanced set 3 phase positive sequence voltages.

The normal operating conditions of the GB AC Grid are defined in **Section 4.**

The data for the 5 Hz bandwidth limit is defined in **Section 5.**

2.2. The GBGF Withstand Mode.

For this mode a GBGF inverter is operating in the conditions that require a design to operate reliably for the three withstand conditions defined in the GBGF Grid Code which are:

- An AC Grid short circuit fault.
- An AC Grid phase Jump angle with values from the **Phase Jump Angle Limit** value up to the possible 60-degree angle change for closing a feeder, see **Section 6**.
- An AC Grid with a RoCoF rate between 1 Hz / s and up to 2 Hz / s.

This operation can be at or below the **Peak Current Rating** value and all the specified GBGF Grid Code requirements apply apart from the 5 Hz bandwidth limit.

Operating a GBGF inverter in the **GBGF Withstand Mode** requires fast changes in the system output voltage and or output phase angle to avoid the system tripping that may also requires the GBGF inverter to produce positive and negative sequence voltages.

A GBGF inverter only remains in the **GBGF Withstand Mode** for a very short time period before returning to the **GBGF Normal Mode** with a bump-less power transient.

A GBGF inverter also has two rating classifications that will be defined in a future Grid Code update.

2.3. The Transmission Stability Service “TSS” rating classification.

The TSS classification is for a commercial product providing a framework for the owner and operator of an item of Plant and Apparatus to contribute to a Transmission System Service, which includes the Stability Pathfinder Service, this will also be defined in a future Grid Code update

The design operates in the **GBGF Normal Mode** for all the normal operating conditions of the GB AC Grid and has a **Peak Current Rating** that is the larger of:

- The **Active Phase Jump power** that is produced by a higher **Phase Jump Angle Limit** rating for the angle defined in **Section 6.**

  This higher **Phase Jump Angle Limit** rating is to ensure that TSS GBGF inverters remain operational for the worst-case phase jump angles in the GB AC Grid at rated voltage conditions, to provide a realisable service to NGESO to enable these systems to replace rotating synchronous generators.
- Peak **Active Inertia power** plus the **Active Damping power** at the Grid Oscillation Value defined in the Grid Code as 0.05 Hz peak to peak at a frequency of 1 Hz.
- The system’s **Peak Current Rating** defined by the supplier.

2.4. The Basic rating classification.

This classification is for non TSS systems.

The design operates in the **GBGF Normal Mode** for all the normal operating conditions of the GB AC Grid and has a **Peak Current Rating** that is the larger of:

- The **Active Phase Jump power** that is produced by a **Phase Jump Angle Limit** rating of 5 degrees, see Grid Code Table PC.A.5.8.2.
- Peak **Active Inertia power** plus the **Active Damping power** at the Grid Oscillation Value defined in the Grid Code as 0.05 Hz peak to peak at a frequency of 1 Hz.
- The system’s **Peak Current Rating** defined by the supplier.

2.5. The most important requirements for a GBGF inverter.

2.5.1. Providing instant Active Phase Jump power.

This important requirement is it provide an instant supply of **Active Phase Jump power** in the **GBGF Normal Mode** when an instant change in the phase angle of the GB AC Grid occurs without any control actions happening in the associated control system.

Systems using fast acting current control loops do not provide the required immediate response which is probably the main difference between GBGF inverters and other Grid forming designs.

A typical system of a GBGF inverter in the **GBGF Normal Mode** is shown on **Figure 2.5.1** that shows how the required instant supply of **Active Phase Jump power** is achieved.

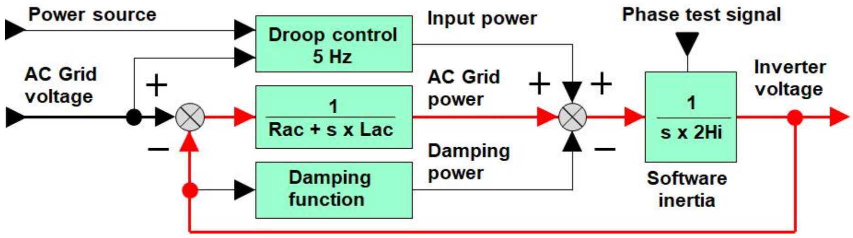

Figure 2.5.1. A typical GBGF Normal Mode system.

The main functions of a GBGF inverter in the **GBGF Normal Mode** are:

- An inverter voltage that has a balanced 3 phase waveform with only positive sequence voltages.
- A software integrating function 1 / (s x 2Hi) to provide the system's software inertia. This function only produces slow changes in the inverter's voltage, with no phase jump transients, when there are changes in the system's net power.

  The exception is the Phase Test Signal that can produce a phase jump angle for testing.
- A software damping function to allow the system's equivalent Damping Factor to be adjusted either in test or on site over a range of at least 0.2 to 5 pu to provide the optimum system for a given location. The equivalent Damping Factor is the Damping Factor of a standard second order system with the same open loop unity gain phase margin.
- The system's AC supply impedance with a real inductance Lac and a real resistance Rac.
- A closed loop, shown in red, with a well damped resonant frequency to ensure that the inverter's frequency tracks the AC Grid's frequency to keep the inverter synchronised to the AC Grid.
- Additional low bandwidth control functions, like the Droop control.

The **Figure 2.5.1** does not need to shows the design and control of the associated energy storage system as the control and the required value of the energy storage are assumed to be correct at the initial design stage. The requirement for these features is defined in **Section 3** which includes this validation test.

The **Figure 2.5.1** is also based on the inverter having the correct rating for the normal operating conditions including supplying the rated reactive power. This means that a simple separate model of the reactive power control can be defined independent of **Figure 2.5.**1 for a frequency domain simulation.

For time domain simulations a reactive control loop model will normally be included in the simulation.

A supplier can use any set of functions to provide a set of equivalent features implemented in the supplier's software and for a specific contract a supplier is required to submit a set of data to NGESO that includes the system's functions for approval.

2.5.2. Providing Active Inertia power.

This important requirement is it provide a supply of **Active Inertia power.**

This is provided by the software inertia in **Figure 2.5.1** plus the required energy store to pass the Energy store rating test, see **Section 3.**

These parameters must be fully defined for producing a viable design.

2.5.3. Providing Active Damping power.

This important requirement is it provide an instant supply of **Active Damping power.**

There are three features that provide **Active Damping Power**:

- The real losses in the Rac supply resistance.
- The damping software function that must be adjustable on site.
- A Software damping control function like the Droop Control function.

The Grid code has nominated a test value for the **Defined Active Damping Power** for a Grid Oscillation Value of 0.05 Hz peak to peak at 1 Hz for rating a GBGF inverter.

2.5.4. Providing a well-defined TIV value.

This important requirement is it provide a well-defined real AC impedance for very short time periods of 0 to at least 100 milliseconds after any power transient, see **Section 8.**

2.5.5. Providing a system resonant mode with adjustable damping.

This important requirement is it provide and adjustable software damping function for the system's AC resonance frequency with a Damping Factor in the range of 0.2 to 5.0.

This enables an installed system to set to the optimum damping value for a specific location.

2.5.6. Reliable operation for TSS GBGF inverters.

This important requirement is to ensure that TSS GBGF inverters remain fully operational for the normal operating condition so that they can be used to replace rotating synchronous generators.

This is defined in **Section 6.**

3. System Black Box performance tests.

3.1. The Phase Jump Angle test.

For a GBGF inverter 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 Lac.
- 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 3.1.**

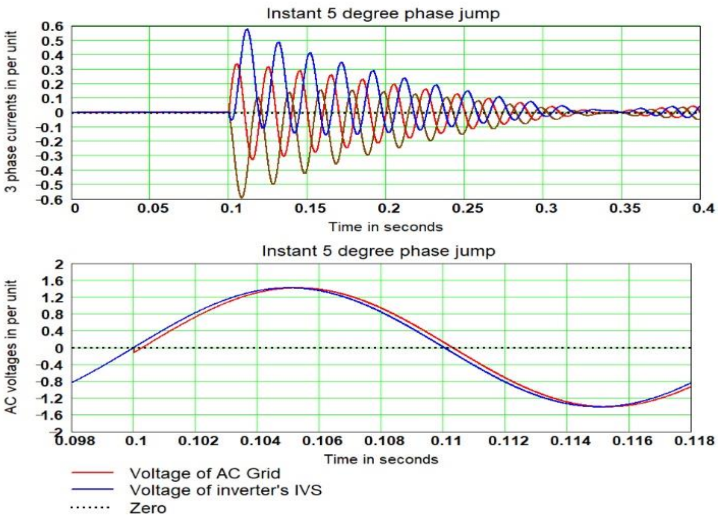

Figure 3.1. Phase jump current transient test.

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 and see **Section 6** for more details on the decaying DC components.

The essential feature is that the phase angle of the inverter's IVS does not change at the start of the transient.

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

This is the most important black box test to validate that any system is a GBGF compliant system.

This test should be repeated using the Phase Test Signal shown on **Figure 2.5.1** 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.

3.2. The RoCoF test.

This is the same test as **Section 3.1** but with a – 1 Hz / s RoCoF rate for the AC Grid's frequency.

This produces a current transient as shown on **Figure 3.2.**

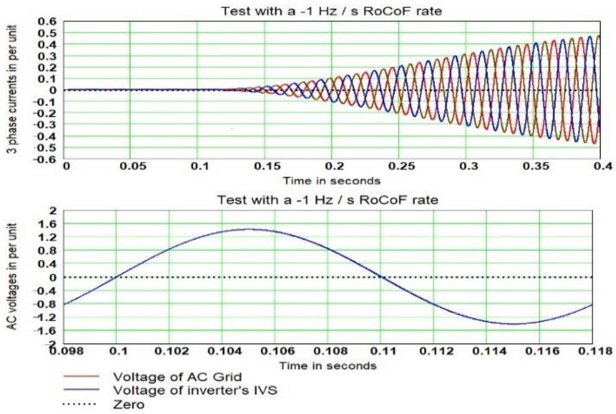

Figure 3.2. RoCoF current test.

The test should be carried out for +ve and -ve RoCoF rates which is a set of 2 tests.

The slow rate of rise of the AC current is the result of the slowly changing phase for a RoCoF test which is why the two recorded voltages have a very small difference.

This slow response is the main reason why the **Active Phase Jump power** is more important than the **Active Inertia power** in stabalising an AC Grid.

3.3. The Resonant frequency and damping test.

This is to apply the standard 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.

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.

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 3.3.**

This frequency domain test is limited to 20 Hz due to cross modulation effects with the 50 Hz main grid frequency.

The **Figure 3.3** is for a NFP test produced in the frequency domain that can plot the NFP plot for test frequencies above 20 Hz.

This test is initially done with all the added control features turned of as shown on **Figure 2.5.1** and with the damping software set to give a Damping Factor of 0.2.

This validates the system's resonant frequency and damping software for one set of the system's parameters.

The test is repeated with all the added control features enable to give the systems full NFP plot.

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.

The results of these test data points can be compared with the system's simulated NFP plot shown on **Figure 3.3** including complying with the five limit lines and Area1.

The GFBPW needs to validate the five limit lines and the Area 1 as correct for GB Grid systems.

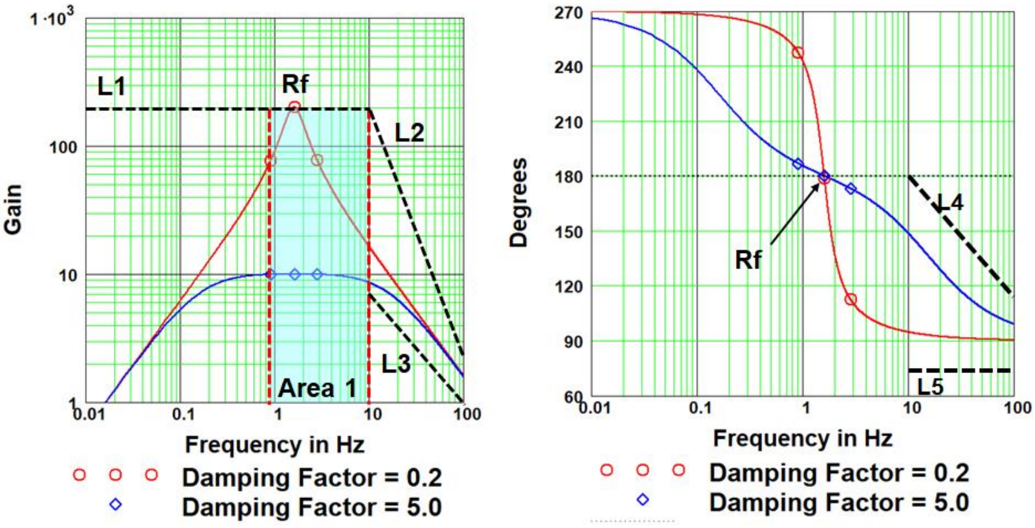

Figure 3.3. The NFP plot test without control functions.

3.4. The Energy store rating test.

This is to validate the control and rating of the associated energy store for the worst-case transient of 50 Hz to 52Hz then to 47 Hz as shown in **Figure 3.4** see Reference [1], Section ECP.A.3.9.4. iv).

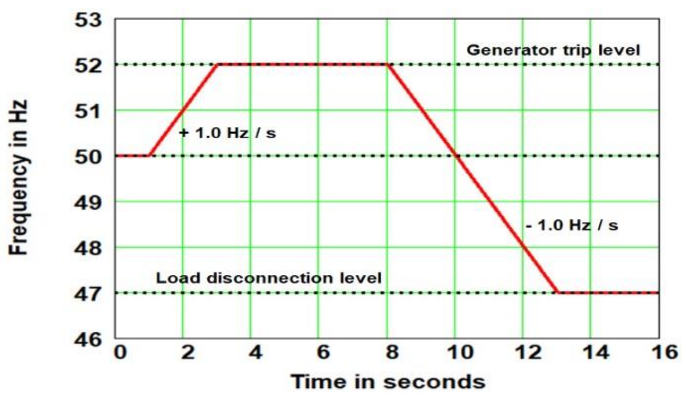

Figure 3.4. Required worst case power and energy response.

This is an operating condition that can arise when there are insufficient AC Grid power reserves.

The rating of the energy store is validated to ensure that the automatic disconnection systems have time to operate. This condition uses the **GBGF Normal Mode** for this condition.

This validation test is to check that a supplier has supplied the correct control and rating of the stored energy for a GBGF inverter by measuring the energy produced.

This rating also ensures that a GBGF inverter can operate reliably for several repeated normal RoCoF events with available power reserves at the SQSS defined operational power limit.

The required energy storage must deliver approximately 20 % of the energy compared with the stored energy in an equivalent synchronous generator when the operating frequency ranges are considered.

The required energy store will require a larger value that depends on the system's design which is why the Hi value for a GBGF inverter cannot be defined by the system's stored energy.

The equation is **Hi = 25 x Active Inertia Power**, in pu, for a RoCoF rate of 1 Hz / s.

The control can be validated in a test laboratory that uses the GBGF control system with a typical inverter that could typically be rated at 1 MW.

The associated energy store must be rated with the appropriate rating for the test inverter.

The energy store's rating for a full-scale system can be approved by using mathematical data sent to NGESO.

3.5. The System's TIV test.

This test is to validate that a GBGF inverter has a well defied TIV impedance.

The test circuit is shown on **Figure 3.5**.

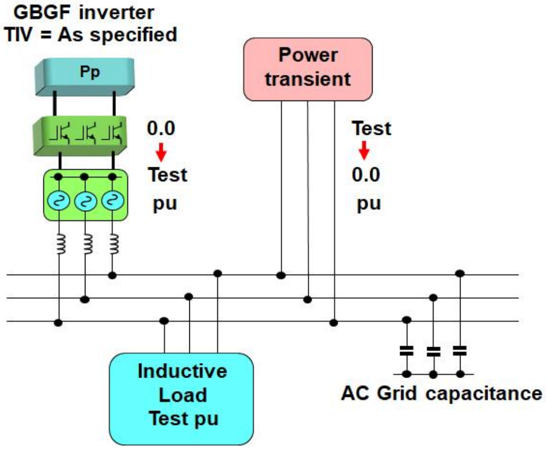

Figure 3.5. The TIV test

The test has an initial condition with a Test pu load flow from the power supply.

The Test pu load flow is set to be the current rating of the GBGF inverter for its **Phase Jump Angle Limit** rating.

The test is to instantly remove the applied power.

The GBGF inverter will immediately respond and produce the same AC power.

The resulting phase angle change is measured and compared with the GBGF inverter's TIV value.

The resulting angle change should be constant for at least 100 milliseconds.

This validates the fundamental property of a GBGF inverter to have a well-defined TIV impedance at the **Phase Jump Angle Limit** rating.

4. The normal operating conditions of the GB AC Grid.

The proposed normal operating conditions are:

- A voltage magnitude within the range defined in the Grid Code. See ECC.6.1.4.
- A voltage unbalance ratio within the range defined in the Grid Code, see ECC.6.1.5.

  The unbalance ratio will require a small power derating for an existing inverter design.
- A frequency within the range defined in the Grid Code of 47 Hz to 52 Hz, see ECC 6.1.2.
- A power factor within the range defined in the Grid Code, see ECC 6.3.2.
- Operating with a RoCoF rate of up to +/- 1 Hz / s, see ECP.A.9.1.9.2.
- Operating with a SQSS defined worst case power transient.

  At present this negative 1.8 GW power transient.

  This is under review to include positive power transients and a possible larger magnitude.
- Operating with a SQSS defined worst case value for the allowed **Phase Jump Angle Limit.**

  This is recommended to be 5 degrees for non TSS GBGF inverters and a larger value is needed for TSS GBGF inverters see **Section 6**. This is essential for the correct current limit rating of all GBGF inverters.

5. The control 5 Hz bandwidth limit.

The latest Grid Code in ECC.6.3.19.3 (v) (d) has the following requirement to:

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.

The reasons for the 5 Hz limit are:

- To avoid the production of a continuous output of sub-harmonic frequencies from the GBGF inverter 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.
- 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

To clarify the Grid Code a revised definition for a “**Control 5 Hz Bandwidth Limit”** is proposed for inclusion in a future Grid Code update that states “**For a GBGF-I operating in the GBGF Normal Mode, any signal that directly affects the amplitude, and or frequency and or phase of the GBGF-I’s output voltage are required to have their bandwidth limited to 5 Hz.”**

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6. The proposed maximum Phase Jump Angle Limit.

This is needed to define the maximum allowed +ve and -ve AC Grid phase jump angle change in each local zone of the GB AC Grid when the SQSS defined worst case power transient occurs.

For **The Basic rating classification** of a GBGF inverter this is recommended to be 5 degrees in Table PC.A.5.8.2.

To clarify the Grid Code the definition for an increased “**Phase Jump Angle Limit”** for TSS GBGF inverters and the existing 5 degrees “**Phase Jump Angle Limit”** for non TSS GBGF inverters is proposed for inclusion in a future Grid Code update.

A higher value is needed for TSS GBGF inverters to ensure that they remain operational for the normal operating conditions of the GB AC Grid. This enables TSS GBGF inverters to reliably replace rotating synchronous generators.

The Grid Code Section in NGESO has requested that the required **Phase Jump Angle Limit** values are defined by the **GFBPW** and listed in the **GFBPW Rating Definition data.**

This will then allow these values to be easily updated in the future based on measured results from the GB AC Grid. The proposed value for the **Phase Jump Angle Limit** is estimated to be in the range of 10 to 20 degrees which avoids any risk of damage to GBGF generators.

The existing NGESO documents do not have any limits on the AC Grid’s phase jump angles as there was no need to do this with synchronous generators.

- A 20-degree **Phase Jump Angle Limit** will produce a 1 pu current change for a system with a typical AC Grid impedance of 0.35 per unit that will require TSS GBGF inverters to have a 2.0 pu current limit margin due to the point on wave decaying DC effects shown in **Figure 6.1** with an instantaneous angle change.
- A10-degree **Phase Jump Angle Limit** will produce a 0.5 pu current change for a system with a typical AC Grid impedance of 0.35 per unit that will require TSS GBGF inverters to have a 1.0 pu current limit margin due to the point on wave decaying DC effects shown in **Figure 6.1** with instantaneous angle change.

Defining the vales for the **Phase Jump Angle Limit jump angle limit** value can be calculated by the GFBPW to add to the **GFBPW Rating Definition data** from the TIV impedance of the GB AC Grid and it is likely that different values will be required for the three transmission voltages.

These values are required to define the current limit of a TSS GBGF inverter and the required extra current must be added to the normal operating current to define the required current limit value.

This will apply to NGESO Constraint Management Units that are also going to supply a TSS ability and to renewable energy systems that want to be a TSS GBGF inverter system.

The NGESO documents do define a requirement for the operating condition of closing a feeder on to the main AC Grid that can give a 60-degree phase jump angle change in the feeder due to the settings of the reclosing protection.

This is a rare local event and is not considered to be relevant to defining the values for the **Phase Jump Angle Limit**.

The **Figures 6.1** and **6.2** are examples of a TSS GBGF inverter for these conditions;

- A phase jump angle change of 10 degrees, with the rise time for the phase angle change to reach its final value of 20 milliseconds for **Figure 6.1** and 1 millisecond for **Figure 6.2.**
- Software based inertia Hi = 10 with an NFP gain plot resonant frequency of 1.07 Hz.
- A following **RoCoF 2** rate of 1 Hz / s.
- AC supply impedance of 0.35 pu.

An optimal design with the same **Active Phase Jump power** and **Active Inertia power** due to the Hi value as shown on the **Figures 6.1** and **6.2.**

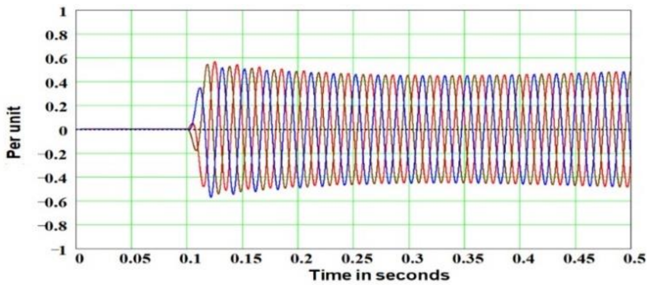

Figure 6.1. Inverter current for a phase change with a 20 millisecond phase rise time.

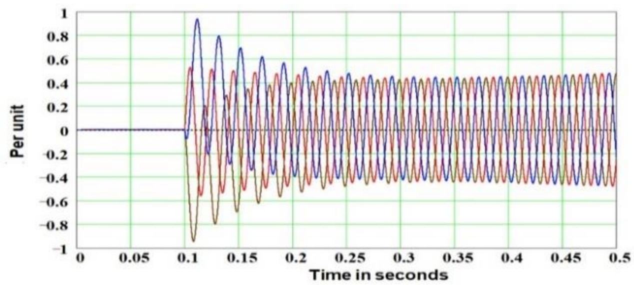

Figure 6.2. Inverter current for a phase change with a 1 millisecond phase rise time.

A three-phase time domain simulation must be used to see these effects that are vitally important for the correct rating of the current limit for GBGF inverter designs and for the validation testing.

The data in **Figure 6.2** has decaying DC components with a different amplitude in each phase that are produced by the point on wave switching effects. These DC components decay at a rate set by the Lac and Rac values and are not significantly affected by the GBGF inverter's control system.

The DC components shown in **Figure 6.2** define the required **Peak Current Rating** of TSS GBGF inverters and the correct current limit rating is essential for TSS GBGF inverters to ensure that they remain in the **GBGF Normal Mode** for the normal operating conditions of the GB AC Grid.

7. The abnormal operating conditions of the GB AC Grid.

7.1. 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 inverters in the local zone will leave the **GBGF Normal Mode** and use the **GBGF Withstand Mode** control for a short time before returning to the **GBGF Normal Mode.**

The GBGF Withstand Mode can be based on the control and response as used by the existing proven PLL based systems or any other viable control system.

For GBGF inverters they should only enter the **Grid Fault Ride Through operating mode** if the inverter's current limit rating is reached and should exit this mode as soon as it is possible to return to the **GBGF Normal Mode**.

This can give an increased AC Grid voltage operating range for operating in the **GBGF Normal Mode.** This complies with the Grid Code **Figure ECC.6.3.19,5 (a)** that only requires operating above the black / red lines.

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.

This angle is not relevant to defining the **Phase Jump Angle Limit.**

For this fault, all synchronous generators will produce reactive power and the large phase angle changes do not produce damaging mechanical transients.

7.2. 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. This large phase jump angle change is not relevant for defining the **Phase Jump Angle Limit**.

The GBGF inverters only have to remain in operation, without tripping, for this abnormal operating condition that can be achieved by using a PLL based control, or similar control, for a very short time period.

This should ideally enable a system to provide a current near to its current limit rating.

7.3. The control for a RoCoF 2 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.

This control is easy to implement by a simple spill-over limit to the **Figure 2.5.1** to ensure that a phase lock to the AC Grid is maintained.

This should ideally enable a system to provide a current near to its current limit rating.

8. The TIV analysis method for AC Grid phase jumps.

The typical circuit used by a Grid Following inverter is shown in **Figure 8.1.**

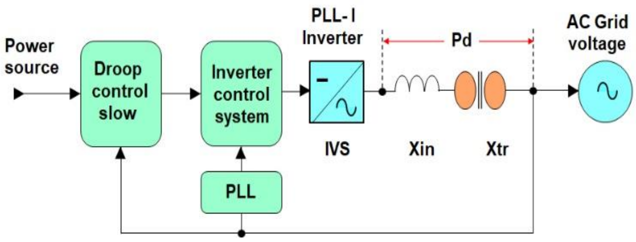

Figure 8.1. Typical Grid Following inverter PLL circuit.

A Grid Following inverter uses PLL control, or a similar technology, that measures the phase angle of the AC Grid's voltages to rapidly change the phase angle of the inverter's IVS voltage to stop changes in the inverter's current by keeping the angle Pd constant during AC Grid power transients.

Figure 8.2 shows the AC Grid current for a Grid Following inverter in response to a change in the phase angle of the AC Grid.

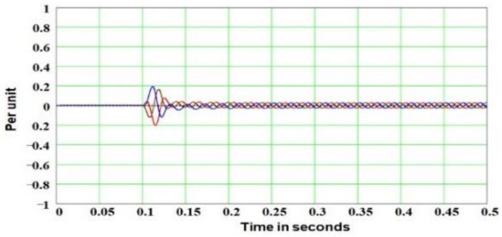

Figure 8.2. Response of a Grid Following inverter.

Figure 8.3 shows the AC Grid current for a GBGF inverter in response to the same change in the phase angle of the AC Grid.

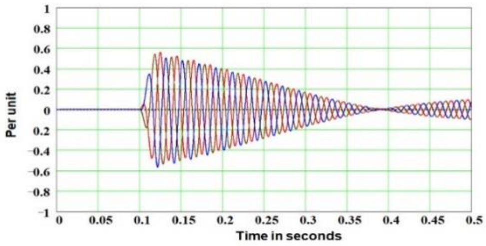

Figure 8.3. Response of a GBGF inverter.

Figure 8.2 has the same initial response as **Figure 8.3** for a few milliseconds then the Grid Following PLL control acts to stop any AC Grid current changes.

These results led to the development of the Transient Impedance Value "TIV" concept which is used to correctly calculate the phase jump angle produced by a power transient in the AC Grid.

A Grid Following inverter has a high impedance after a phase jump angle change which stops the inverter from supplying **Active Phase Jump power** to stabilise the AC Grid which is why it was necessary to develop the TIV concept.

The TIV impedance is the same as the normal AC Grid system's impedance values except the impedance value for existing inverters using a Grid Following PLL type of control are set to be an open circuit, in other words their impedance is more or less infinite.

The consequences for the GB AC Grid are shown in **Figures 8.4 & 8.5** for the power and phase angle changes that happen in milliseconds.

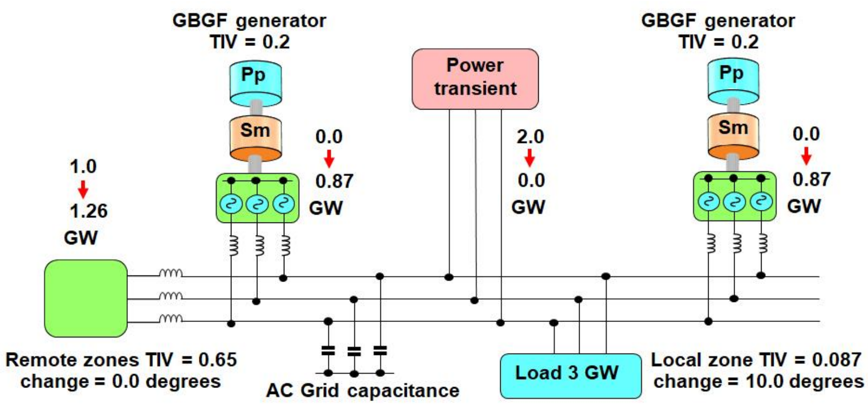

Figure 8.4. The GB AC Grid with two GBGF generators.

For the system shown in **Figure 8.5** the 2 GW power loss transient results in both GBGF generators immediately supplying 0.87 GW with a time response set by the AC Grid's capacitance.

The net TIV value is 0.086 in the local zone which gives an AC Grid's phase jump angle of 10 degrees.

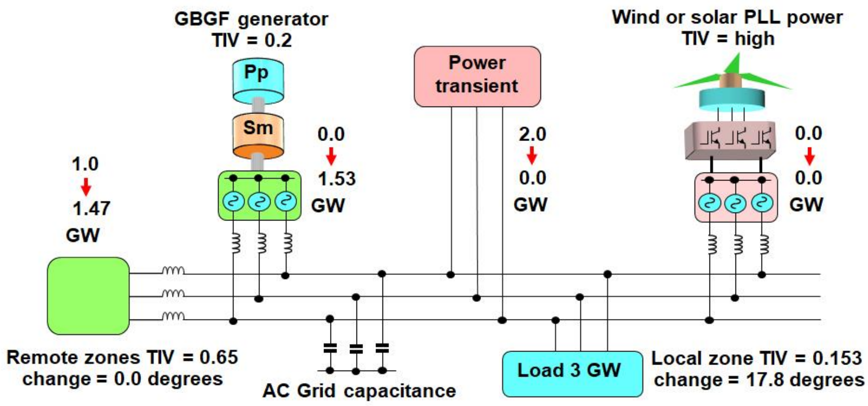

Figure 8.5. The GB AC Grid with One GBGF generator and one PLL inverter.

For the system shown in **Figure 8.5** the 2 GW power loss transient results in the single GBGF generator immediately supplying 1.53 GW as the PLL renewable system does not supply any extra power despite having similar AC impedances.

The net TIV value is 0.153 in the local zone which gives the AC Grid's phase jump angle of 17.8 degrees.

This shows that Grid Following PLL inverters act to reduce the stability of an AC Grid by causing increased phase jump angles for an AC Grid power transient.

The short circuit current produced by Grid Following PLL inverters is useful for providing fast fault current to enable the AC Grid's protection systems to operate.

However, the short circuit current of Grid Following PLL inverters does not provide stability for an AC Grid system which is only provided by GBGF inverters.

It is important that the TIV concept is used to predict the change of AC Grid's phase jump angles for power transients to ensure that the correct equipment is fitted in each local zone of the GB AC Grid. The TIV concept must be used in calculating the AC Grid's phase jump angles.

9. Design of the GB AC Grid.

With the existing AC Grid with synchronous generators the magnitude of the change in the local phase angle depends on the power transient and the local zone's TIV.

The resulting **Active Phase Jump power** and energy are initially supplied from the rotational inertia of the synchronous generators in the AC Grid's local zone, which is why the frequency of the frequency in the local zone of the AC Grid starts to fall.

This fall of the AC Grid's frequency then results in the synchronous generators supplying the **Active Inertia power** to limit the frequency change in the local zone to the **RoCof 2** rate that has been seen to occur based on the data from the Enhanced Frequency Control Capability PMU data.

The frequency of the total AC Grid will continue to fall at the **RoCoF 1** rate until extra primary response power is produced by generators in the local and remote zones of the AC Grid increasing their power output that continues until the frequency is stabilised.

The same effect occurs for a sudden power increase transient that produces a rising local zone **RoCoF 2** rate. This can occur for a trip at the input end of a HVDC link.

NGESO are producing the requirements for the TSS GBGF Units to stabilise the local zones of the GB AC Grid and these requirements apply to TSS synchronous generators and TSS GBGF inverters.

A key requirement for a stable GB AC Grid is to install the correct TSS Units in each local zone of the GB AC Grid to meet the maximum allowed values for the **Phase Jump Angle Limit** and the **RoCoF 2** rate. This then ensures that the rest of the GB AC Grid see significantly smaller transient disturbances.

In the November 2021 meeting of the GFBPW it was agreed that all TSS GBGF inverters must remain operational for all the normal operating conditions of the GB AC Grid, defined in **Section 4**, without reaching a current limit. This is called the **GBGF Normal Mode** for TSS GBGF inverters and is essential to prevent a sudden and cascade failure of the GB AC Grid.

This is to enable the operators of the GB AC Grid to select either TSS GBGF generators or TSS GBGF inverters without affecting the stability of the GB AC Grid for all normal operating conditions.

When TSS GBGF inverters are operating in the **GBGF Normal Mode** their performance can be described by the **GBGF Normal Mode** model, see **Section 2**, to provide a set of responses that are in line with the GBGF Grid Code and are also virtually identical to the responses of a GBGF generator.

A supplier can choose to use the **Figure 2.5.1 GBGF Normal Mode** model and ideally either the GFBPW or NGESO should supply a public domain set of simulation equations for the **GBGF Normal Mode** model.

A supplier can alternatively choose to use any viable control system to implement **GBGF Normal Mode** provided it meets the requirements of the GBGF Grid Code. The supplier's control system can then be validated by comparing its results with the results of the **Figure 2.5.1**.

The required current limit for GBGF inverters directly depends on the magnitude of a phase jump angle and to correctly design and rate GBGF inverters requires that the normal operating condition for the GB AC Grid are fully defined including the normal operating limits for RoCoF rates and phase jump transients.

The existing NGESO documents do not have any limits on the AC Grid's phase jump angles as there was no need to do this with synchronous generators. The need to add a defined limit for phase jump angles in the GB Grid Code has been discussed with the Grid Code section of NGESO and it is agreed that this will be a future action by NGESO.

10. GBGF inverter validation, site testing and site recording.

The control of a GBGF inverter, for a range of tests, can be validated in a test laboratory that uses a supplier's GBGF control system with a typical inverter that could typically be rated at 1 MW.

For the test the associated energy store must be rated with the appropriate rating for the test inverter.

The energy store can be validated on site by using a programmed output power / time profile based on the **Figure 3.4** to deliver the rated **Active Inertia power** for the given time periods.

When an AC Grid short circuit fault occurs the inverter's supply transformer has to operate under very low voltage conditions during the fault. When the fault is cleared a sudden voltage step is applied to the inverter's transformer that can cause it to go in to magnet saturation which produces abnormal even AC supply harmonics and very distorted output voltages at the inverter's terminals.

The **Figure 10.1** shows an example of the waveforms that can occur measured for a real system.

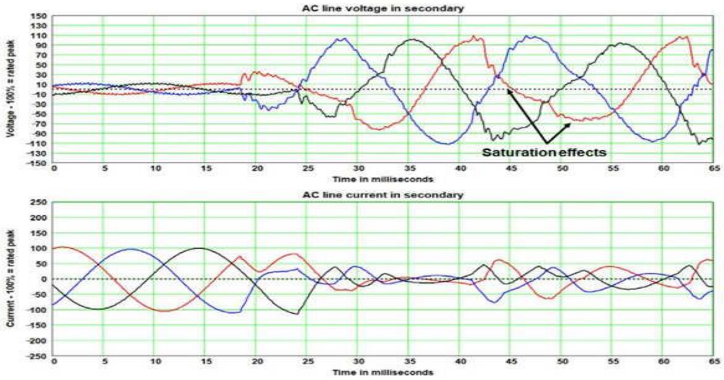

Figure 10.1. Short circuit waveforms.

The very distorted output voltages at the inverter's terminals will require the GBGF inverter to remain in the **GBGF Withstand Mode** until these effects disappear within a few mains cycles.

These transformer saturation effects will normally result in lower AC supply transient overvoltage conditions when compared with GBGF generators.

The Enstore's simulation of this condition requires the use of a nonlinear transformer model that produces the waveforms caused by transformer saturation.

To replicate the correct operation for the validation of the AC Grid short circuit in a test laboratory the GBGF inverter's transformer ideally needs the same saturation levels of a full-scale system.

For wind farms the validation of full-scale systems is normally carried out a full-scale special test site that can be used to test GBGF inverters.

For site testing of a GBGF inverter connected to the GB AC Grid the phase test signal, shown on **Figures 2.5.1 & 10.2**, can be used to apply a programmable AC Grid phase jump that fully replicate a phase jump in the AC Grid.

The phase test signal can also be used for on-site periodic system validation.

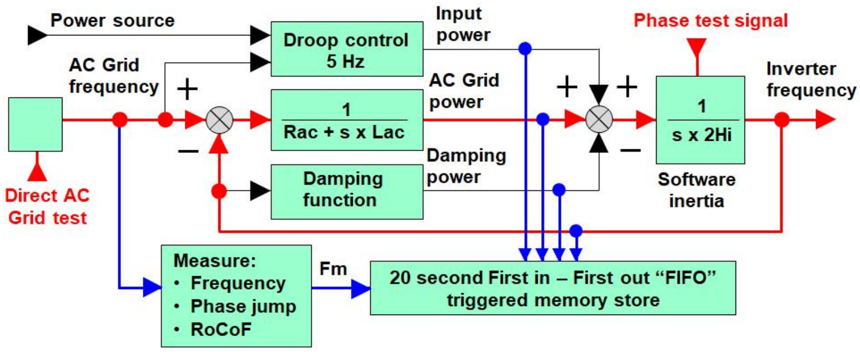

Figure 10.2. Site testing and recording.

To fully validate a GBGF inverter requires testing producing AC supply transients that only happen during system faults and a GBGF inverter requires the use of a PMR system operating independently of the GBGF inverter's SIC system to capture and store the resulting transients for a follow-up analysis.

The GBGF Grid Code has a requirement to measure and record the frequency of the AC Grid with a high immunity to AC Grid Phase Jumps angles plus the value of any significant Phase Jump angle transients, see Grid Code ECC.6.6.1.9 that states:

- In order to accurately monitor the performance of a Grid Forming Plant, each Grid Forming Plant shall be equipped with a facility to accurately record the following parameters at a rate of 10ms:
  - System Frequency using a nominated algorithm as defined by The Company.
  - The ROCOF rate using a nominated algorithm as defined by The Company based on a 500ms rolling average.
  - A technique for recording the Grid Phase Jump Angle by using either a nominated algorithm as defined by The Company or an algorithm that records the time period of each half cycle with a time resolution of 10 microseconds.

For accurate measurement of the phase changes requires a system sampling at a rate near to 100 kHz and Enstore has data on possible measuring algorithms.

11. Notes on nonlinear control systems.

There are 3 common high bandwidth control methods used by existing inverters:

- Fast acting Phase Locked Loops "PLL" and equivalent control systems.
- Fast acting D and Q current control loops and equivalent control systems.
- Fast acting Synthetic AC impedance control loops and equivalent control systems.

These, and any other control methods, can be used for implementing GBGF inverter control systems provided the **Control 5 Hz Bandwidth Limit** is applied when the GBGF inverter is operating in the **GBGF Normal Mode.**

There are no bandwidth limits in the **GBGF Withstand Mode**.

12. Modification record.

Issue	Date	By	Details
001	01/08/2022	Enstore	• Initial issue
002	9/08/2022	Enstore	• The section 12 on the Proposed changes to the Grid code is now in a separate document