Enstore

Document. **The Enstore guide to GB Grid Forming technology – 002.**
Issued to. **Unrestricted issue.**
Signed by. **E A Lewis -** Eric Lewis Company director **Enstore**.
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0. Acknowledgements.

The data and image for the tank shown on **Figure 5.10** was provided by **Fisher Tank.com.**

The image of the Ammonia generator was provided with the permission of **Mitsubishi Heavy Industries, Ltd.**

The data for the **Enstore Figure 5.9** was extracted from the **NGESO** data portal.

The data for the **Enstore Figures 4.1, 4.2, 4.3, 5.7, 7.1** and **7.2** was taken from data in the **NGESO GC0137** public domain documents.

1. Commercial conditions:

1. This text has a reference "**The Enstore guide to GB Grid Forming technology – 002"** hence called **The Data.**
2. **The Data** has been independently produced by **Enstore** based on the **GBGF** Grid Code**.**
3. **The Data** presents **Enstore's** views on the effects of Grid Forming Technology on the GB AC Grid.
4. **Enstore** has no liability in any way whatsoever for any use of **The Data** by any company or person**.**
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Signed by…**Eric A Lewis** … Eric A Lewis BSc (Eng) CEng MIET- Company Director. 021-04-2022.

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2. Acronyms.

BEIS	UK Government Department for Business, Energy and Industrial Strategy.
EFCC	**NGESO** project for Enhanced Frequency Control Capability.
ENTSO-E	European Network of Transmission System Operators for Electricity.
ESS	Energy Storage System.
FIFO	First in First out storage system with a defined storage time period.
FSM	Frequency Sensitive Mode.
GBGF- I or GBGF-S	GB Grid Forming technology for – I inverters or – S synchronous generators.
GFBPW	GB Grid Forming Best Practice Workgroup.
H	The **NGESO** definition of stored energy = MWs per MVA and the per unit "pu" value of the software inertia.
HVDC	High voltage DC**.**
Ig(ω)	AC Grid current in the frequency domain.
IPR	Intellectual Property Rights.
IVS	The Internal voltage source of either a generator or an inverter.
Lac	The inductance of the AC supply that includes all inductors and transformers.
NFP	Network Frequency Perturbation plot as defined by **ENTSO-E**.
NGESO	National Grid Electricity System Operator.
NOP	Normal Operating conditions of the GB AC Grid.
OFGEM	GOV UK Office of Gas and Electricity Markets.
Pd	Phase difference angle.
PLL	Phase Locked Loop control or any similar phase based fast control used by the existing inverter systems.
PWM	Pulse Width Modulation system.
Rac	The resistance of the AC supply.
Rf	Resonant frequency of a **GBGF** system.
RoCoF - 1 & - 2	Rate of Change of Frequency – 1 in the main AC Grid zones and – 2 a higher value in a local AC Grid zone.
SPF	Stability PathFinder.
SQSS	Security and Quality of Supply Standard.
TIV	Transient Impedance Value.
Vg(ω)	AC Grid voltage in the frequency domain.
Vivs(ω)	Inverters **IVS** voltage in the frequency domain.
VSM	Virtual Synchronous Machine.
Xin	Impedance of the inverter's inductor.
Xtr	Impedance of the inverter's AC transformer.
ω	Angular frequency = 2 x Pi x frequency in Hz.

3. The 4 stages in the development of the GB Grid Forming systems.

Stage 1. The NGESO Virtual Synchronous Machine expert group.

The VSM expert group was started in April 2018 because the GB AC Grid was becoming less stable with increasing levels of inverter based renewable power.

The initial aim was to develop a high level VSM specification and establish the viability of the technology. In particular one of the aims was to provide **Active Inertia power** from inverter systems based on using the Virtual Synchronous Machine "**VSM**" technology and the wide range of public domain data on **VSM** systems producing synthetic inertia.

The **NGESO Virtual Synchronous Machine expert group** stability studies showed that when a sudden loss of generated power occurs that the current in the remaining generators increases very rapidly.

This causes a very rapid change in the **Phase Jump angle** of the AC Grid's voltage in the local zone of the power transient and the **Phase Jump angle** increases until the AC Grid's power balance is restored.

In the existing GB AC Grid, the extra **Active Phase Jump power** is provided by power taken from the generator's inertia, which results in a Rate of Change of Frequency "**RoCoF 2"** rate in the local zone of the AC Grid.

This action is the most important requirement for having a stable AC Grid which is why the **VSM** technology was re-assessed and the **Stage 2** actions started in late 2019.

Stage 2. Minimum Grid Code Specification for the Provision of a GB Grid Forming Capability.

The **GC0137** expert group produced the GB Grid Forming "**GBGF"** Grid Code to define the requirements for the supply of **Active Phase Jump power** plus **Active Inertia power** and **Active Damping power** by **GBGF- I** inverters.

The **GBGF** Grid Code was approved by **OFGEM** on the 31 January 2022 and implemented into the Grid Code on 15th February 2022. This data contains a summary in Appendix 18 describing the **GBGF** technology that was produced by **Enstore**, see **Reference 1**.

The **GBGF** Grid Code is a non mandatory minimum specification for the implementation of **GBGF** technology and the **Stage 3** actions were stated to provide the associated application and modelling data.

Stage 3. The initial work of the NGESO Grid Forming Best Practice Workgroup "GFBPW".

This group started in July 2021 to produce data on the implementation of the **GBGF** technology.

The typical circuit used by a Grid Following inverter using a Phase Locked Loop **"PLL"** control is shown in **Figure 3.1.**

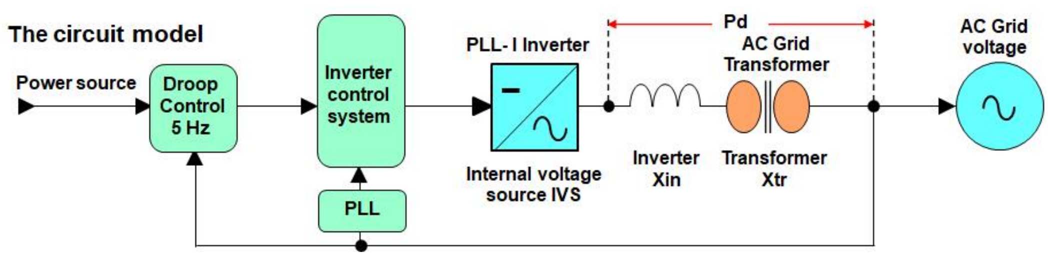


Figure 3.1. Typical Grid Following inverter PLL circuit

The Grid Following inverter uses a Phase Locked Loop **"PLL"** control, or a similar technology, that measures the phase angle of the AC Grid's voltages and uses this data to rapidly change the phase angle of the inverters Internal Volage Source "**IVS**" change to stop changes in the inverters current by keeping the angle **Pd** constant during AC Grid power transients.

The Figure 3.2 shows the AC Grid's current for a Grid Following inverter compared with a Grid Forming inverter to show the difference in the inverter's response to a change in the phase angle of the AC Grid.

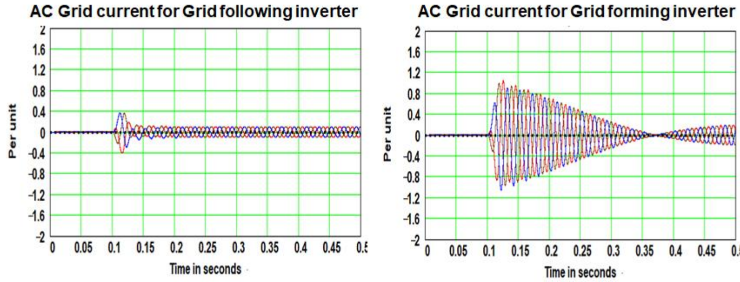


Figure 3.2. response of Grid Following versus Grid Forming inverters.

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 and is also the basis of the **TIV** impedance. The **TIV** impedance is the same as the normal AC Grid system's impedance values except the impedance value for existing inverters based on Grid Following **PLL** control are set to be an open circuit, in other words the impedance is more or less infinite.

The short circuit current produced by Grid Following **PLL** inverters is not relevant to calculating the **TIV** and the **TIV** concept explains why existing inverters based on Grid Following **PLL** technology do not provide stability for an AC Grid system and how AC Grid stability is provided by **GBGF- I** inverters.

Stage 4. The latest work of the GFBPW.

The **NGESO** are also developing Stability Pathfinder "**SPF**" systems using the **GBGF- I** inverter technology that can reliably replace synchronous generators and maintain full AC Grid stability.

In the November 2021 meeting of the **GFBPW** it was agreed that **SPF GBGF- I** inverters must remain operational for all AC Grid Normal Operating "**NOP**" conditions without reaching a current limit. This has been called the **Linear Operating Mode** for **SPF GBGF- I** inverters.

This concept is essential for the system operators of the **NGESO** AC Grid system to be able to select the optimal mix of **GBGF-S** generators and **SPF GBGF- I** inverters for efficiently running the GB AC Grid system without any concerns for the systems stability. To implement the **Linear Operating Mode** for **SPF GBGF- I** inverters requires a range of important **Items** to be implemented by the **NGESO.**

Enstore produced a document for **NGESO** in January 2022, see **Reference 4**. that proposed that the following **Items** should be implemented:

- **Item 1**. An operational limit to define the maximum allowed **AC Grid's Power transient** for positive and negative power changes in the GB AC Grid for rated voltage condition.
- **Item 2.** An operational limit to define the maximum allowed positive and negative AC Grid **Phase Jump angle** change in each local zone of the GB AC Grid when **Item 1** occurs.
- **Item 3.** The operational limit should be retained that defines the maximum allowed AC Grid's **RoCoF** rate in each local zone of the GB AC Grid when **Item 1** occurs. This is called the **RoCoF 2** rate.
- **Item 4.** To have a revised standard for calculating AC Grid's **Phase Jump angles** using the **TIV** impedance concept for the **Item 1** condition.
- **Item 5.** To have a full definition for the **NOP** conditions**.**
- **Item 6.** To require **SPF GBGF- I** inverters to have the correct overload margin to ensure that they stay in their **Linear Operating Mode** for all the **NOP** conditions.

  This is a significant requirement as a 20-degree AC Grid's **Phase Jump angle** can require a current limit margin of up to 2 per unit. This was validated by the Aalborg University and GE Power presentations made to the **GFBPW** in the spring of 2022. This is less than the 60- degree **Phase Jump angle** discussed in GC0137 which is a **Non-Linear Operating Mode**, see next page.
- **Item 7.** For **NGESO** to install in each local zone of the GB AC Grid the appropriate equipment to implement items 1 to 3 by either **SPF GBGF- I** inverters or rotating compensation systems.

The **Reference 4** document was discussed with the **NGESO** and the following was agreed:

- That the existing GB Grid Code did not have any limits on the AC Grid's **Phase Jump angles** as there was no needed to do this with synchronous generators apart from the abnormal operating condition of closing a feeder on to the main AC Grid that could give a 60-degree **Phase Jump angle** change due to the settings of the **ACCB** reclosing protection system.
- That the **GFBPW** should discuss the six Items and make a firm proposal to the **NGESO** for an update to the GB Grid Code and to give data for **SPF GBGF- I** inverters.
- That **NGESO** would then update the required documents that could take approximately one year. This would need to be progressed through the Grid Code Governance arrangements as provided for in the Governance Rules of the Grid Code.

The **GFBPW** are now discussing these topics that have not been finalised at the date of this report.

These Items have enabled **Enstore** to produce data on the resulting consequences in the GB AC Grid system that are:

- That in the future the GB AC Grid may have very little synchronous power generation from the Nuclear stations and Hydro storage stations and that most power will come from inverter-based systems. For this future system, the AC Grid must remain stable for the worst case **SQSS** defined power transients of both polarities for load, HVDC link and generation power transients.
- That when the equipment for **item 7** is installed in each local zone of the GB AC Grid that no extra inverter-based inertia will be needed.
- That either new or existing wind power systems can be supplied as:
    - Designs using the existing **PLL** Grid Following technology to supply reliable power during the **NOP** conditions but these are then not **SPF units**.
    - Designs using the existing **PLL** Grid Following technology to supply reliable power during the **NOP** conditions with an extra **SPF GBGF- I** inverter in parallel to become a **SPF** compliant design, see **Figure 5.3**.
- That the same applies to either new or existing renewable power systems including solar power systems and **HVDC** link systems, see **Figure 5.4**.
- That **HVDC** link systems must have a limit on their maximum power per link in line with **Item 1** to avoid a power transient above the design limits for the GB AC Grid**.** This is very relevant to the development of multi terminal wind power offshore systems.

The result of implementing the **Items 1** to 7, especially for **Item 5**, is that a simple **standard linear model** of a **GBGF- I** inverter can be produced for a system operating within the **NOP** conditions.

The **standard linear model** for a **GBGF- I** inverters simplifies the large-scale modelling of **SPF GBGF- I** inverter systems, renewable energy systems and **HVDC** systems for the **NOP** conditions.

The **standard linear model** also enables each supplier to develop their own product, without any **IPR** concerns, and provides a standard format for the validation of a supplier's design versus the **standard linear model**.

Enstore has developed a version of this model, see **Figure 4.6**, to produce a full range of performance responses as shown on **Figure 9.10**.

Enstore also believes that the use of **Optimal SPF units** that provide equal ratings of **Active Phase Jump power** and **Active Inertia power** is important in minimising the implementation cost for the GB AC Grid.

This set of proposal are now being reviewed by the **GFBPW** that will be published when they are finalised

The following sections describe these concepts in more detail and contains a set of parameters for the 400 kV GB AC transmission system that are based on the **Enstore's** simulation and a different set of values will be needed for different transmission and distribution systems.

4. The operation of the GBGF technology in the Linear Operating Mode.

When a power transient occurs the location is called the AC Grid's local zone. The results of the **EFCC** project have shown that the resulting frequency changes in the AC Grid's local zone are significantly larger when compared with the frequency changes in the other AC Grid's remote zones.

The results of a power transient are significantly smaller in the remainder of the AC Grid called the remote zones. This effect is shown on **Figure 4.1** which is important for the simulation of a large AC Grid system as it is only necessary to accurately simulate the effects in a local zone with a simpler model for the remote zones.

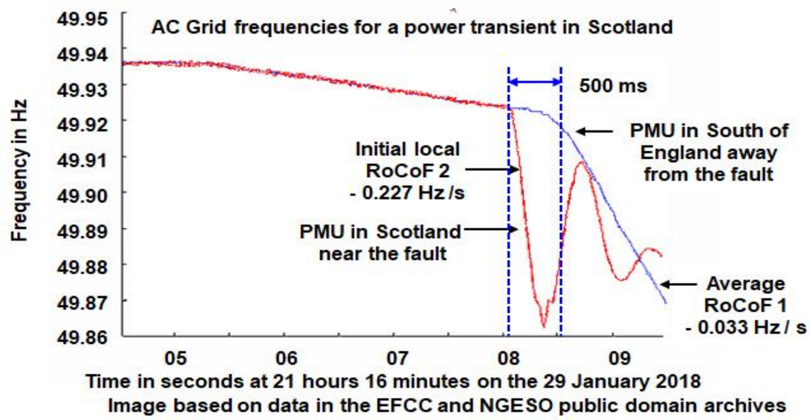


Figure 4.1. Effects of a power transient.

The power transient in an AC Grid's local zone has a fast **RoCoF 2** rate frequency transient that lasts for about one second and then after this time period, the AC Grid's local zone and all the other AC Grid's remote zones converge to have a slower **RoCoF 1** rate frequency transient defined by the total AC Grid inertia.

The right-hand side of **Figure 4.2** shows the set of the GB AC Grid's local zones proposed by the **EFCC** project together with the proposed GB **HVDC** links.

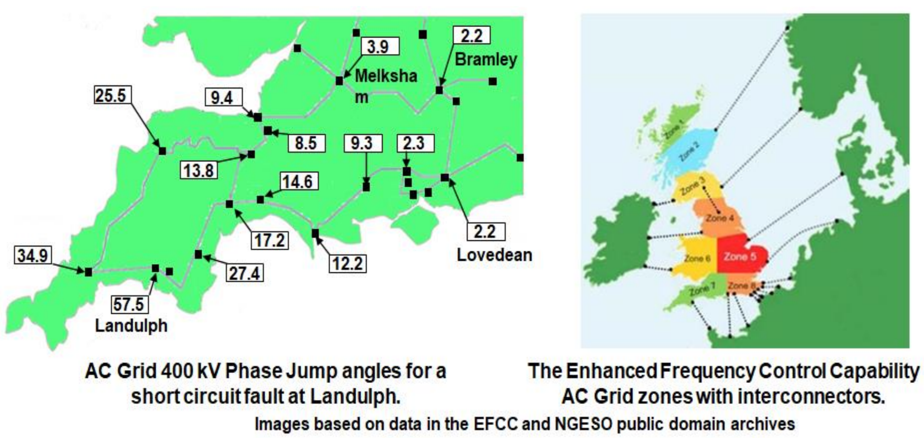


Figure 4.2. UK AC Grid's local zones.

The left-hand side **Figure 4.2** also shows that the **Phase Jump angles** for short circuit in the GB AC Grid rapidly reduce away from the local zone of the AC Grid.

The **HVDC** links can either import or export power and the trip of an **HVDC** link can produce a significant **RoCoF 2** rate with either falling or rising AC Grid frequency transient. This requires a bidirectional power rating for **SPF GBGF-** I inverter systems.

Each AC Grid's local zone is fitted with the appropriate equipment to provide stability for an AC Grid operating within the defined **NOP** conditions by having sufficient **Active Phase Jump power** equal to the Power Transient at the maximum **Phase Jump angle** plus sufficient **Active Inertia power** to limit the **RoCoF 2** rate to the maximum allowed value.

The **Active Phase Jump power** provided by **SPF** systems is only required for approximately one second as shown on **Figure 4.1** to stabilise the AC Grid's frequency in the local zone of the AC Grid. After this time the total AC Grid starts to provide the required **Active Inertia power** and **Active Response power** to stabilise the frequency of all the zones of the AC Grid. It is also worth of note that Active Response Power (which could include Dynamic Containment services (frequency response delivered in 1 second of the frequency fall) can have a significant effect here, which is important in limiting the capability requirements of the Grid Forming Plant.

The **NOP** condition data proposed by **Enstore** based on the **Enstore's** AC Grid model for any local zone of the **NGESO** 400 kV transmission system are:

- A maximum AC Grid power transient up to the **SQSS** defined operational design limit of +/- 2 GW.
- A transmission AC Grid with a minimum **TIV of** 0.17 pu on a 2 GW base.
- AC Grid's **Phase Jump angle** up to a **SQSS** defined **Maximum Operational Design limit**. +/- 10^0.
- AC Grid's **Phase Jump angle** with a rise time that can be less than 5 ms.
- AC Grid's **RoCoF 2** rate up to a **SQSS** defined operational design limit of +/- 1 Hz / s.
- AC Grid's voltages within the normal range of +/- 10 %.
- AC Grid's voltages with negative sequence voltages defined by the GB Grid Code.
- An AC Grid's frequency oscillation with an amplitude of 0.05 Hz peak to peak at a frequency of 1 Hz as defined in the GB Grid Code. This is used as part of the peak current rating.

The equipment required to provide a stable AC Grid can be a mixture of **GBGF- I** inverters and rotating machines.

For a **GBGF- I** inverter to replace a synchronous generator it must provide the same stability for all the **NOP** conditions and remain in its **Linear Operating Mode** without reaching its current limit rating.

This will normally need a significant current rating of approximately double the **Active Phase Jump power** for the proposed **NOP** condition data due to the decaying DC point of wave components shown in **Figure 4.7**.

The performance of a real 560 MW **GBGF-S** generator is shown on **Figure 4.3.**

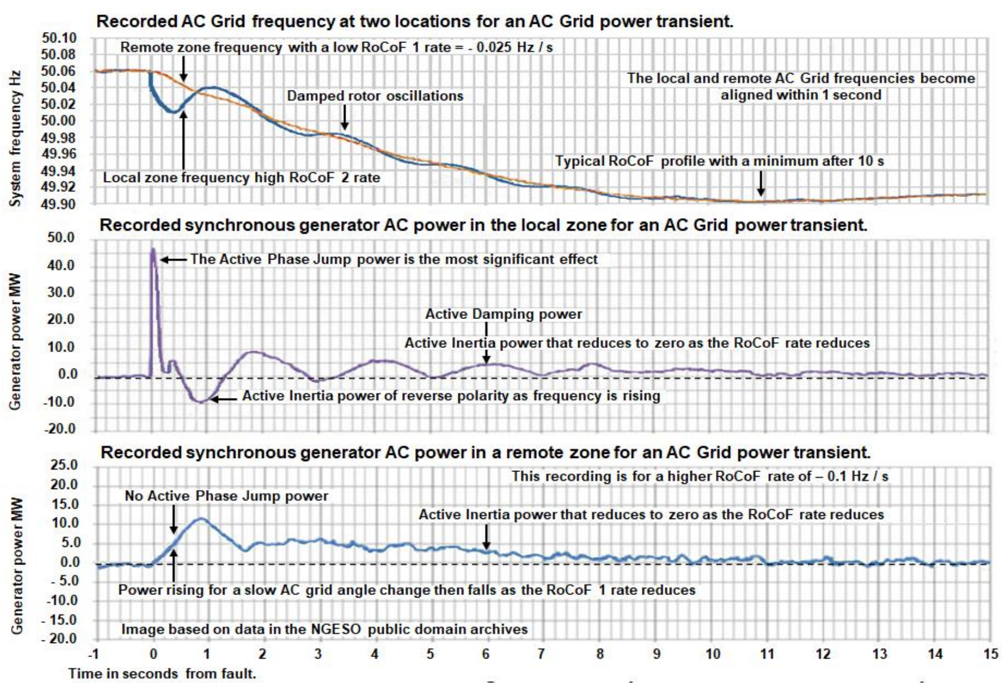


Figure 4.3. The performance of a real 560 MW GBGF-S generator.

The top graph shows the local and remote zone frequencies of the AC Grid. This shows how the local zone **RoCoF 2** rate becomes aligned with the rest of the AC Grid's **RoCoF 1** rate, within approximately one second.

The middle graph is the power produced by a 560 MW synchronous generator in the local zone of the AC transient. This has a very large short pulse of **Active Phase Jump power** followed by a lower level of **Active inertia power** and **Active Damping power**.

The lower graph is the power produced by a 560 MW synchronous generator in a remote zone of the AC transient. This does not have any **Active Phase Jump power** and has a slowly rising level of **Active inertia power**. The MW scale on the lower graph is different to the MW scale on the middle graph.

The **Figure 4.4** is the normal linear simulation model of a **GBGF-S** generator that is based on the Andrew Roscoe model published in the **GFBPW** data.

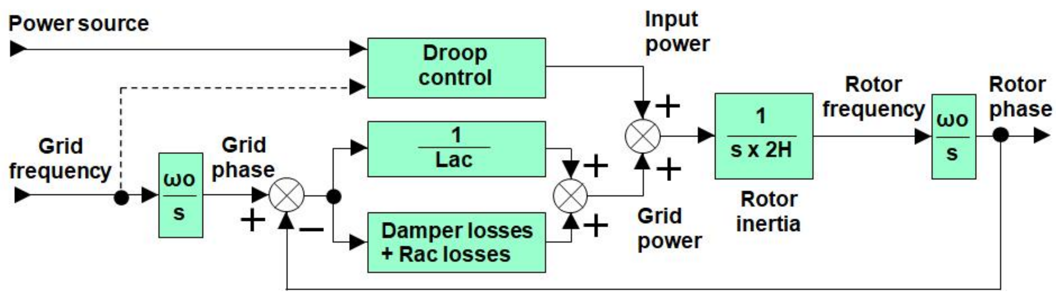


Figure 4.4. Linear model of a GBGF-S generator.

The **Figure 4.4** is based on Phase being the integral of frequency which is correct for **GBGF-S** generators but gives wrong results for **GBGF- I** inverters that do not have this limitation.

The **Figure 4.4** has a closed loop action that has an inherent resonant frequency with a low level of damping.

The **Figure 4.4**. does have a simulation term to add the damping that comes from the resistance of the AC supply and the action of the pole face damper windings of the **GBGF-S** generator.

The **Figure 4.5** shows how a **GBGF- I** inverter can replicate the operation of a synchronous generator.

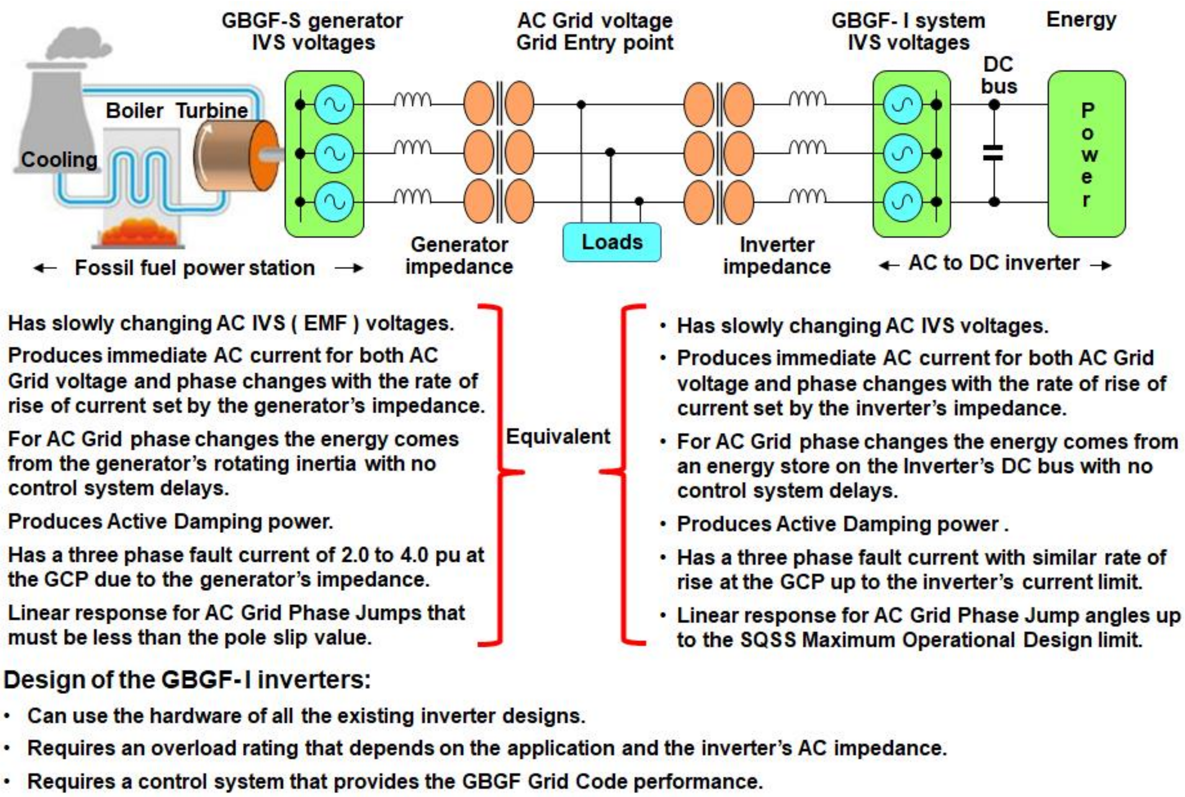


Figure 4.5. Essential requirements of a GBGF- I inverter.

A **GBGF- I** inverter has an **IVS** that only produces positive sequence voltages that change slowly to give the same dynamic response when compared with a synchronous generator with same rating parameters.

The slowly changing inverter's **IVS** means that a **Phase Jump angle** in the AC Grid will produce an instant supply of **Active Phase Jump power** without any action required by the **GBGF- I** inverter's control system.

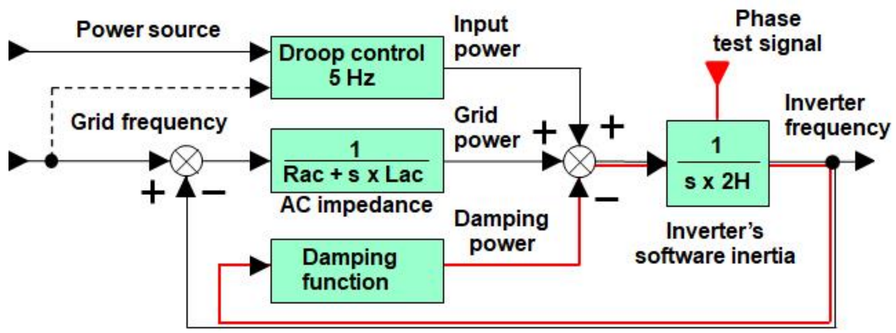
To ensure the correct operation of the inverter's **IVS** a bandwidth limit of 5 Hz is applied to external control systems and **PLL** controls are not used which gives the **GBGF- I** inverter a very high immunity to AC Grid instability effects.

If the AC Grid has negative sequence voltage components this will result in similar magnitudes of negative sequence currents flowing in both the **GBGF-S** generator and the **GBGF- I** inverter. This requires a small rating margin for **GBGF- I** inverters.

For distribution systems a typical **GBGF-S** generator produces a typical short circuit current of 6 pu at the generator's terminal but in transmission systems the extra generator transformer impedance reduces the typical short circuit current to 3 pu at the transmission system AC Grid entry point.

This difference is very important and applies equally to **GBGF- I** inverter systems with the result that **GBGF- I** inverter systems for a transmission connection are significantly less affected by AC Grid **Phase Jump angles** when compared with distribution connected **GBGF- I** inverters.

This operation of the **GBGF- I** inverter means that the **standard linear model** shown on **Figure 4.6** can be used for Transmission AC Grid modelling for all **NOP** conditions and all suppliers can also validate their specific design versus the **standard linear model** for all the **NOP** conditions.



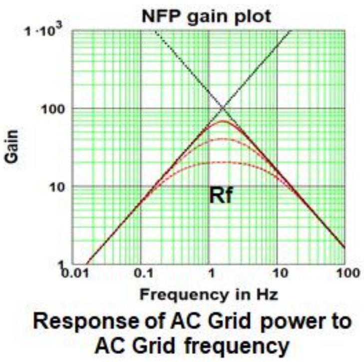


Figure 4.6. Standard GBGF- I inverter model.

The main parts of the **standard linear model** are:

- An integrating function **1 / (s x 2H)** to provide the systems software 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.
- The 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 ensure 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 inverter's **IVS** only change slowly to produce **Active Phase Jump power** and give a very stable AC system.

It is proposed that a **standard linear model** will be fully defined and that suppliers will be able to implement an equivalent control in their own **IPR** software, see **Reference 5**.

The **standard linear model** with the **NFP** plot is used by a supplier to submit an initial proposal to the **NGESO** at the start of a specific project that must meet the defined minimum and maximum resonant frequency **Rf** limits.

The **Section 8** provides more data on **NFP** plots.

To avoid the modelling of the energy storage system of the simple model an assumption is made that the supplier will include the required value of energy storage. This is validated as part of the final submission of a system to the **NGESO** for approval, see **Section 7 item (iv)**.

The systems performance, without Droop control, is defined by a **NFP** plot as shown on **Figure 4.6** that has a resonant frequency **Rf** that is defined by the **Lac** and **H** parameters.

The **NFP** plot on **Figure 4.6** also shows the effect of varying the systems Damping function.

The **NFP** plot is normally produced in the frequency domain and the **standard linear model** for a **GBGF- I** inverter can also be simulated in the time domain to produce the results shown on **Figure 4.7** by using the **Enstore's** software model with these parameters:

- Software based inertia **H** = 10 with an **NFP** plot resonant frequency of 1.08 Hz.
- A **Phase Jump angle** of 20 degrees with two rate of rise values.
- AC supply impedance of 0.35 pu.

The **H** value of a **GBGF- I** inverter is defined by the **Active Inertia power** produced for a **RoCoF 2** rate of -1 Hz / s as the size of the associated energy store can give very misleading results if it is used to define a system's **H** value. The minimum rating of the energy store is approximately 20 % of the stored energy in an equivalent synchronous generator.

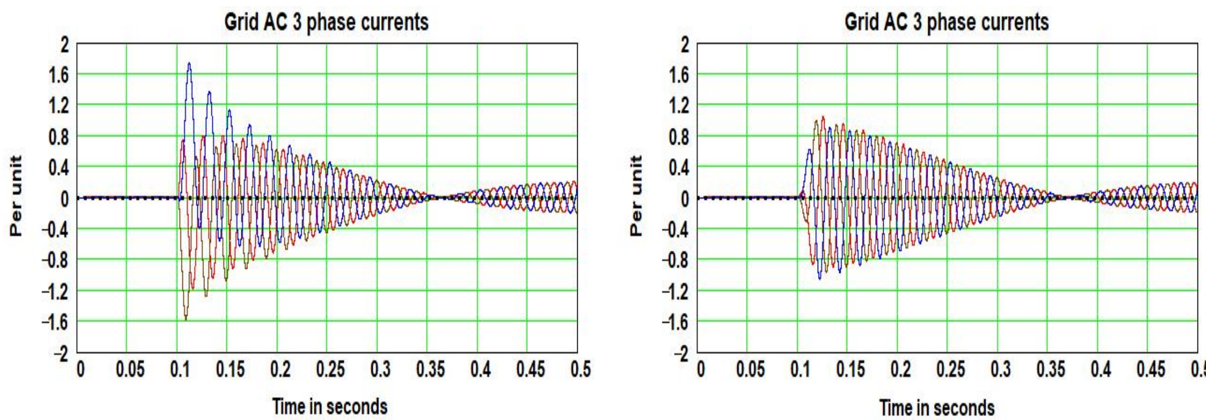


Figure 4.7. GBGF- I inverter required current limit transient rating.

On the **Figure 4.7** the Left-Hand set is for a 20-degree **Phase Jump angle** applied in 1 millisecond and the Right-Hand set is for the **Phase Jump angle** applied over 20 milliseconds.

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 **SPF GBGF- I** inverter designs and for the validation testing.

The Left-Hand set of waveforms shows the **Active Phase Jump power** that has decaying DC components with different amplitude in each phase. These DC components decay at a rate set by the **Lac** and **Rac** values and are not significantly affected by the **GBGF- I** inverter's control system.

The DC components will occur in a real system and this defines the required peak current of **SPF GBGF- I** inverters. The correct current limit rating is essential for **SPF GBGF- I** inverters to ensure that they remain in the linear mode for the **Maximum Operational Design Phase Jump angle**.

The extra rating ratio between a system with and without the DC components is a maximum of 2:1.

5. Application data for the GBGF technology in the Linear Operating Mode.

The **Active Phase Jump power** always happens at the start of a transient in a local zone and this limits the initial **RoCoF 2** rate and takes power from the inertia stores in the local zone which is why the frequency falls. This action is shown on the simulated **Figure 5.1**

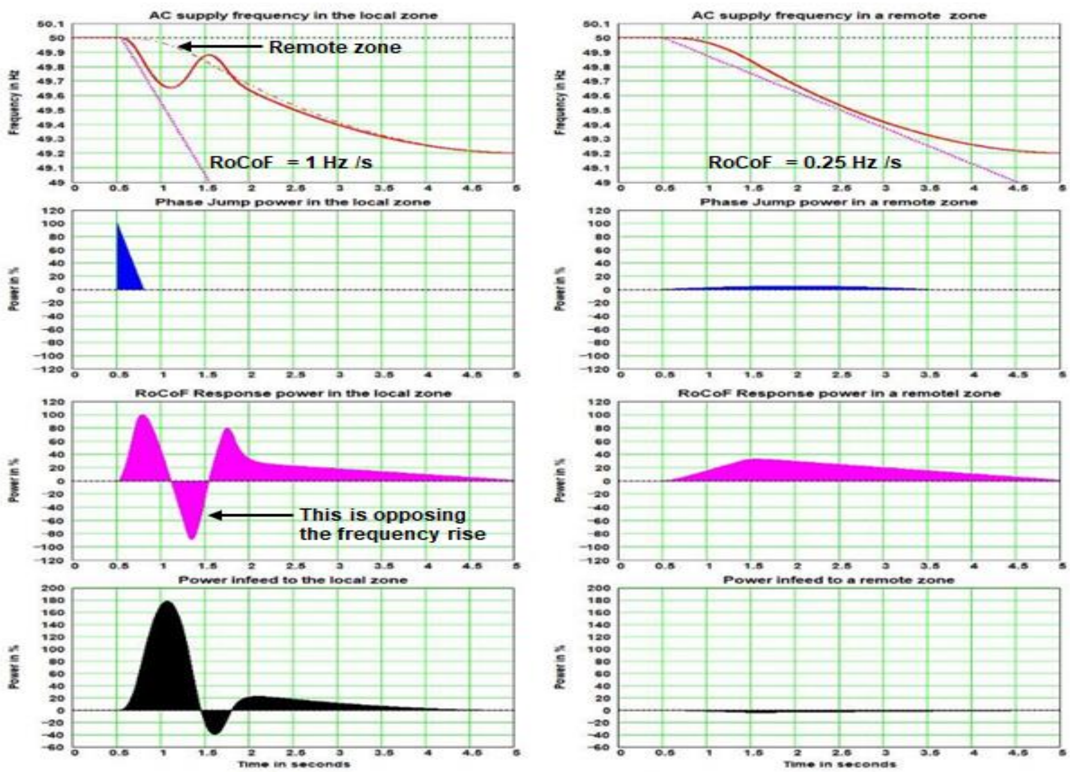


Figure 5.1. AC Grid's power transients.

On **Figure 5.1** for the equipment in the remote zones the amplitude of the **Phase Jump angle** is significantly reduced by the AC Grid's impedance compared with the local zone. The **Phase Jump angle** in the remote zone also have a slower rate of rise that results in very low **Active Phase Jump power** requirements in the remote zones.

The remote zones are dominantly responding to the average AC Grid's **RoCoF 1** rate that provides the **Power Infeed** into the local zone. The **RoCoF 1** rate will typically be 0.25 Hz / s or lower.

The equipment in each local zone has to be rated to supply the **Active Phase Jump power** at a rating equal to the largest predicted power transient in the local zone. This equipment in each local zone also has to be rated to supply the **Active Inertia power** at the same rating.

The **Figure 5.1** shows that the **Active Phase Jump power** is equally and vitally important compared with the **Active Inertia power** in having a stable AC Grid. This change of emphasis has only recently occurred and is not reflected in most **VSM** developments.

The **SPF GBGF- I** inverter specification requires that the system does not go in to current limit for a defined **Phase Jump angle** to keep all of the AC Grid in the **Linear Operating Mode**.

The **Power Infeed** is also a new concept which causes the local zone frequency to rise and is a significant power transient.

Both the **Active Phase Jump power** and the **Active Inertia power** need to be equal to the power transient in the local zone which is the basis of the **Optimum SPF unit rating.**

The design of a typical **SPF GBGF- I** inverter **ESS** system is shown on **Figure 5.2.**

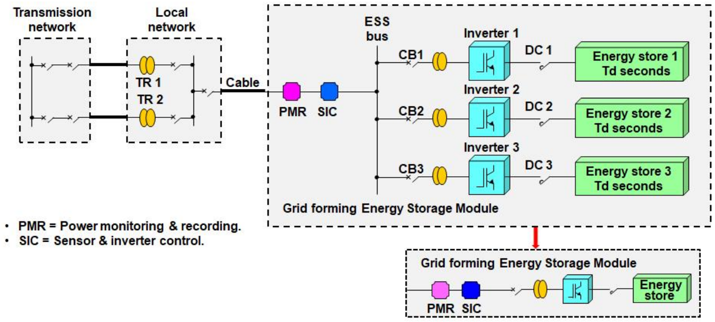


Figure 5.2. Typical SPF GBGF- I inverter ESS system.

A typical **SPF GBGF- I inverter** Energy Storage Module uses:

- Many identical **GBGF- I** inverters in parallel to give a system with redundancy and high availability as each parallel system has its own AC Circuit Breaker ”**CB**” and DC Contactor “**DC**”.
- The DC contactor is essential with Lithium batteries that must not be fully discharged but the DC contactor is not essential with Ultra capacitor storage systems.
- Inverters, each is typically 1 MW and for a stability system Td is typically 10 seconds or longer as needed. This system shown delivers 3 MW for 10 seconds.
- The use of a medium voltage **GBGF- I** inverter with a 5 kV DB bus with Lithium based batteries is very difficult to implement as the batteries cannot be discharge for maintenance access, unlike Ultra capacitors.

For a system design to supply the Stability Path Finder service the use of Ultra capacitors on a medium voltage **GBGF- I** inverter with a 5 kV DB bus, or even higher, will give the most viable system.

The design also requires a Power monitoring & recording “**PMR**” system plus an advanced Sensor and Inverter Control System “**S & IC**”, see **Section 8**.

The design of a proposed **SPF GBGF- I** inverter wind power system is shown on **Figure 5.3.**

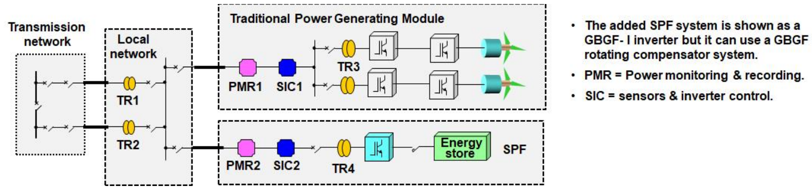


Figure 5.3. Proposed SPF GBGF- I inverter wind power system.

This uses an extra **SPF** system added to a Grid Following wind power system that will deliver a constant AC power in to the AC Grid for all **NOP** conditions. The parallel system is needed as the current limit rating for the **SPF GBGF- I** inverter rating is too high for the existing inverters.

This concept simplifies the systems simulation as the two parts can be independently simulated and the same concept can be used for an **Energy Storage** system and a **HVDC** system as shown on **Figure 5.4**.

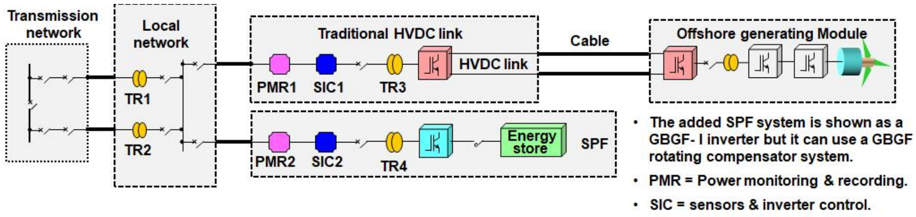


Figure 5.4. Proposed SPF GBGF- I inverter HVDC system.

When **GBGF- I** inverters are used for the **Figures 5.1 & 5.2** the systems can be designed to provide equal ratings for the **Active Phase Jump power** and **Active Inertia power** at the rated operating conditions to minimise the overall cost of the **GBGF- I** inverter **SPF** equipment.

For the proposed **NOP** value of 10 degrees for the **Maximum Operational Design limit** for the **Phase Jump angle** the rating for an **Optimal SPF unit** using either **GBGF- I** inverters or **GBGF-S** generators is:

- A 400 kV transmission AC Grid with a minimum **TIV** = 0.17 pu on a 2 GW base.
- This is a **TIV** based short circuit current of 17 kA.
- A maximum power transient of 2 GW.
- A **GBGF** inverter rated for a current equal to 2 GW.
- An equipment AC supply impedance of 0.35 pu.
- To operate without tripping for an instantly applied AC Grid's **Phase Jump angle**.
- A peak current rating of 1 pu to avoid tripping due to the DC components of the **Phase Jump angle**.
- To produce an average **Active Phase Jump power** of 0.5 pu.
- To produce an **Active Inertia power** of 0.5 pu for a **RoCoF 2** rate of +/- 1 Hz / s set by the **H** value.
- To produce the defined value of **Active Damping power** for an AC Grid's frequency oscillation with an amplitude of 0.05 Hz peak to peak at a frequency of 1 Hz.

The equation for the required optimum **H** value is:

- **H = (AIP x 25).**
- **AIP** is the **Active Inertia power produced** for a **RoCoF 2 r**ate of +/-1 Hz / s in pu of the installed rating.
- This gives a required optimum **H = 0.5 x 25 = 12.5.**
- This is an **NFP** plot resonant frequency of 1.0 Hz which complies with the proposed **NFP** plot limits.

Many proposed **SPF GBGF-S** generator systems may not provide this magnitude of **Active Inertia power** that will then require extra equipment to be installed by **NGESO**.

This may apply when Synchronous Compensators, also called Synchronous condensers Capacitors or Synchronous Capacitors, are installed to add **Active Phase Jump power** as the standard designs may have low **H = 2** value. This also applies when an existing synchronous generator is used without its power turbine.

This is leading to Synchronous Compensators being installed with added flywheels to increase the **H** value but this may not provide the required **Active Damping power**.

The system can use either a **SPF GBGF- I** inverter or a **SPF GBGF-S** machine and there are a wide range of **GBGF-S** machines that can provide the **SPF** ability as shown below and in the **Enstore's BEIS** report, **Reference 3**. The **Figure 5.5** shows how Synchronous Compensators can be updated to provide the features of an **Optimal SPF unit**.

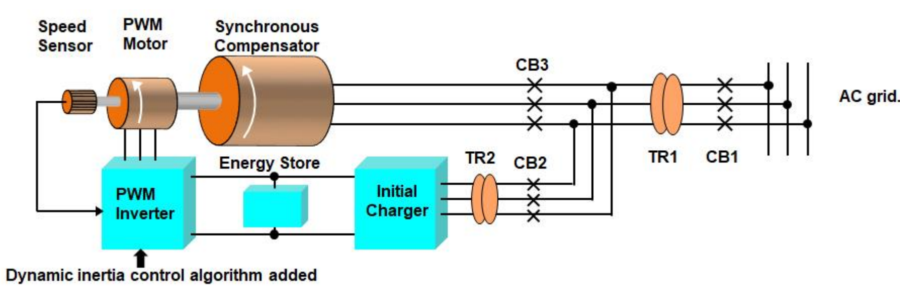


Figure 5.5. Optimal SPF GBGF-S Synchronous Compensator.

The normal run up motor is replaced by a **PWM** Motor and **PWM** inverter that provides these features:

- To run up and synchronise the system to the AC Grid.
- To add the required **Active Damping power**.
- To increase the **H** value by a factor of typically 5:1, depending on the rating of the base compensator.
- To assist in the recovery of the AC Grid's frequency by adding **Active Inertia power**.

The system uses a **Dynamic inertia control** algorithm that can increase the systems **H** value by a factor of up to 5:1 depending on the short-term rating of the **PWM** motor which enables a very small **PWM** motor to be used. This algorithm has been used in industry to dynamically alter the inertia of rotating mechanical parts when they are subjected to applied torque changes without any need for feedback on the value of the changes in the applied torque change.

For this application the system's **H** value is increased without needing any sensors connected to the AC Grid.

The Initial charger is needed to start the system and it can then be turned off and the energy store is then discharged and recharged via the synchronous compensator.

The **Figure 5.6** is a way of providing an **Optimal SPF GBGF-S** generator with an optimum high **H** value.

The high inertia rotating stabiliser uses a synchronous generator that is run up to speed by the Stator Inverter via **ACCB2**. The generator is then synchronised to the AC Grid so that **ACCB 1** can also be closed and **ACCB 2** opened.

The generator is then directly on line in its normal operation mode to provide **Active Phase Jump power** plus **Active Inertia power** and **Active Damping power**.

When a power transient occurs this system initially acts to directly stabilise the AC Grid as an **Optimal SPF GBGF-S** generator as it is design to supply high levels of both **Active Phase Jump power** plus **Active Inertia power.**

When the frequency of the AC Grid is starting to recover the levels of the **Active Phase Jump Power** plus **Active Inertia powers** reduce and the system closes **ACCB2** and controls the Stator inverter to bring the current in **ACCB 1** to zero.

Then **ACCB1** is opened and the system is then acting with the High inertia rotating stabilizer directly connected to the AC Grid.

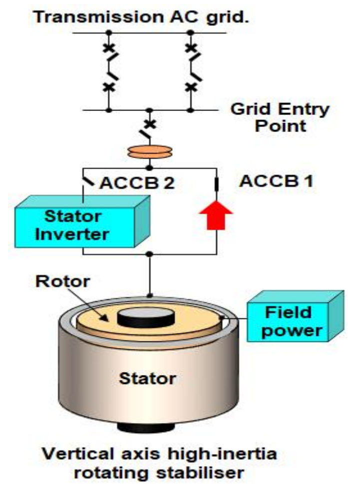


Figure 5.6. High inertia rotating stabiliser.

The system then acts as an **Energy Storage System** that can extract extra power of either polarity from the machines rotor that is able to change its speed as it is not synchronised to the AC Grid and this extra power is used to help the AC Grid recover by adding **Active Control Based power** and **Active Damping power**.

The Stator inverter can delay the recharging of the flywheels stored energy until the AC Grid's frequency has recovered. For this design the Stator invert can use either **GBGF- I** inverter technology or existing **PLL** base inverter technology.

In **Enstore's** opinion all the **SPF** equipment should be procured as equipment with a long in service life similar to a power station.

The **GBGF** Grid Code has a number of required control actions shown on **Figures 5.7.**

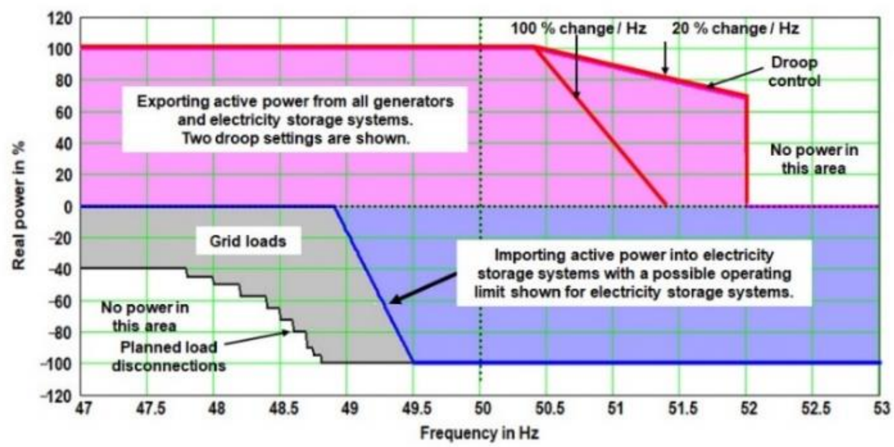


Figure 5.7. Control actions for a GBGF- I inverter.

There are limits on the input and output power as shown on **Figure 5.7**. The new feature is the limit on the power input for frequencies below 49.5 Hz. This is to ensure that the automatic load disconnection systems operate at the frequencies shown on the **Figure 5.7**.

The **Enstore's BEIS** report, see **Reference 3**, also has data on the energy storage requirements for the reliable operation of an AC Grid system without fossil fuel generation and without the need to pay constraint payments to renewable energy systems.

The systems for **SPF GBGF- I** inverters require a dedicated energy store that is able to supply the energy to meet the power transient defined in **Section 4.7 item (iv)** which is an extremely unlikely event.

The **Optimal** energy storage system for this requirement, in **Enstore's** opinion, are Ultra capacitors using carbon nano film technology. This requirement provides **SPF GBGF- I** inverters with an energy store capable of supplying several more normal frequency **RoCoF 2** rate events and this allows the energy store to be recharged once the AC Grid's frequency has recovered to the normal operating range.

The GB AC Grid will also require a distributed energy storage system to supply the maximum AC Grid's power transient up to the **SQSS** defined operational design limit within a time delay of approximately one second which is the basis of the **NGESO** Dynamic Containment service.

The **NGESO's Dynamic Containment's** storage service is required to supply a defined power within one second for a time period of two hours to provide time to secure replacement power after a power transient and there are two main design options:

- To use existing **PLL** base inverters with a 1 pu peak current rating to only supply the specified power for the **Dynamic Containment** service.
- To use a **SPF GBGF- I** inverter system with a 2 pu peak current rating to ensure that the system can independently provide the **Dynamic Containment** service and the **Active Phase Jump power** plus the **Active Dynamic Containment power**.

The GB AC Grid will also require a distributed energy storage system to supply the required GW hours of power on a daily basis to deal with the inherent daily load cycle demand variations. The **Enstore's BEIS** report recommends that this equipment should be procured as equipment with a long in service life similar to a power station which rules out Lithium-Ion batteries. The **Enstore's BEIS** report recommends the use of a new topology of flow cell systems that only need two large storage tanks per system. This can then be used as part of the **NGESO's** Dynamic Containment service see **Figure 5.8.**

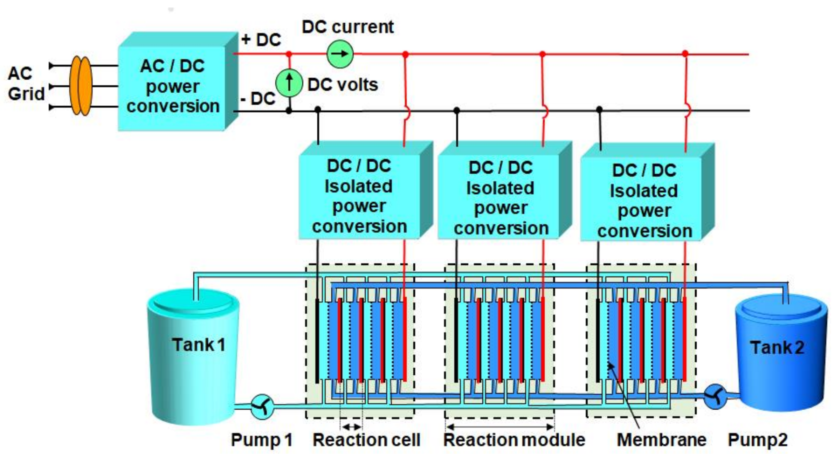


Figure 5.8. Proposed Vanadium Flow Cell system.

For a high efficiency the operating voltage of a **Reaction Module** of a **Flow Cell** system is approximately 50 volts DC to minimise circulating DC currents between individual **Reaction Cells**.

This DC voltage is too low for connecting to the AC to DC power converter and many designs used several sets of **Reaction Modules** plus storage tanks in series to provide a higher system operating DC voltage.

This gives many storage tanks operating at different DC voltages which is not viable for large systems.

The **Figure 5.8** uses DC / DC isolated power converters to provide a system with:

- Many **Reaction Modules** in parallel to give a high-power system.
- Only need two storage tanks.
- Provides the optimum voltage for the AC / DC power converter.
- Can be expanded to store energy for very long time periods by adding extra storage fluid.
- The two storage tanks can be grounded to earth for maximum safety.
- The same Vanadium storage fluid is used in both tanks and at each side of the **Membrane** which means that a pin hole fault in a membrane does not corrupt the storage fluid.
- Energy storage at the molecular level to give essentially unlimited numbers of deep operating storage cycles based on the Vanadium storage system.
- A very safe storage fluid that can be indefinitely recycled.

The **Enstore's BEIS** report also contains data on the need for very long duration storage measured in **GWdays** to deal with seasonable renewable energy generation variations, see **Figure 5.9**, that is data from the spring of 2022. This is very important as the **HVDC** links shown on **Figure 4.2** may not be able to provide a significant level of imported power if the associated countries also have a similar power shortage. The **HVDC** links can export power when there is a surplus of renewable generation to avoid curtailment costs.

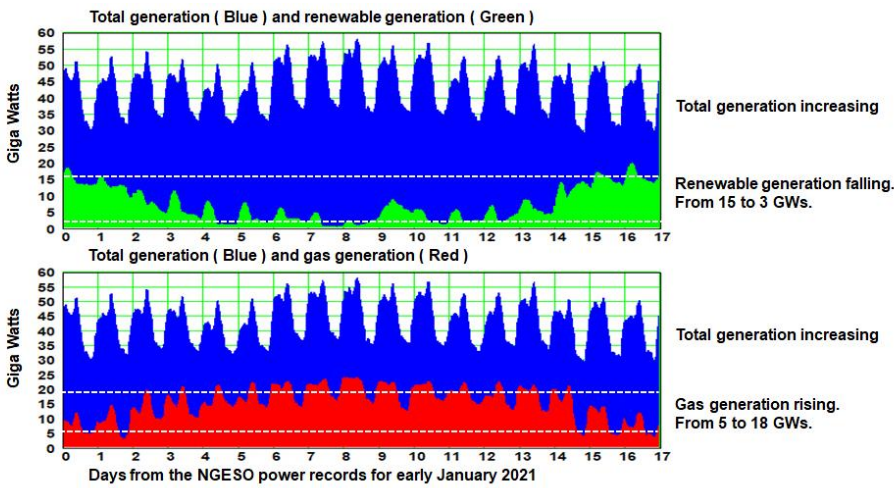


Figure 5.9. Actual GB power data spring 2022.

The **Enstore's BEIS** report recommends the use of a new topology based on storing Ammonia especially as the tank storage systems are in validated use at the required **GW days** of storage see **Figure 5.10**.

Figure 5.10. Typical large Ammonia storage tank.

The large proven Ammonia tank design shown in **Figure 5.10** stores 30,000-ton API 620 anhydrous ammonia in a storage tank that is 170 feet diameter and 98 feet high. The Ammonia is stored as a liquid at -33 degree C to be at atmospheric pressure. This has advantages when compared with Hydrogen stored at -253 degree C.

The tank was produced and installed by **Fisher Tank.com** in North Dakota who kindly supplied this image and at a power of 1 GW the tank contains an energy equal to 170 GWh at an estimated cost of 132 £ / MWh.

Thirty similar tanks like this will provide 30 GW and 5100 GWh which is only approximately 0.5 % of world Ammonia production that indicates that Ammonia systems are viable for long duration winter storage.

The design of a proposed ammonia-based power station is shown on **Figure 5.11.**

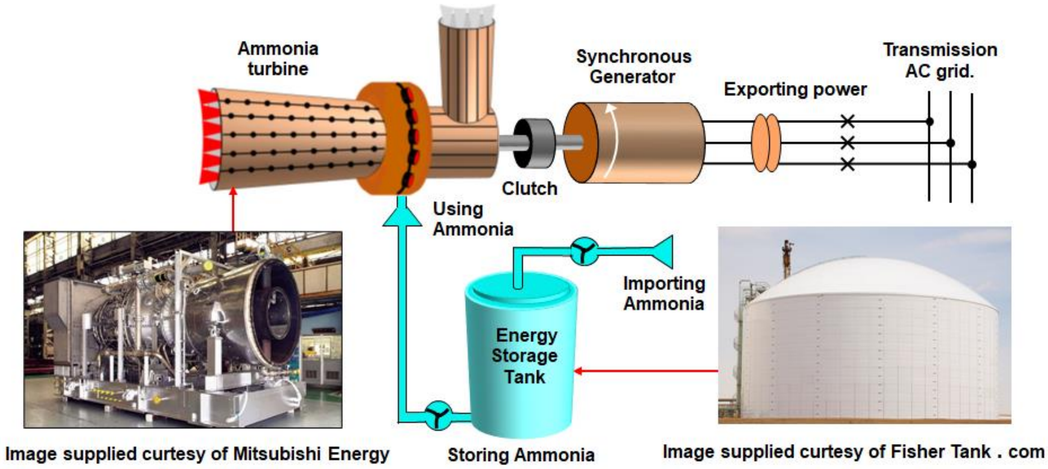


Figure 5.11. A proposed Ammonia based power station.

This power station directly uses the Ammonia in a gas turbine that is being developed by **Mitsubishi Energy** with a proposed in-service date of around 2025 with a 40 MW rating based on the existing **Mitsubishi Energy** model H-25 Series 40 MW gas turbine**.**

The design has a mechanical clutch so that the synchronous generator can be connected to the AC Grid when the Ammonia turbine is not in use to provide **Active Phase Jump** and **Active Inertia power.**

There are a range of additional developments that can be implemented as shown on **Figure 5.12.**

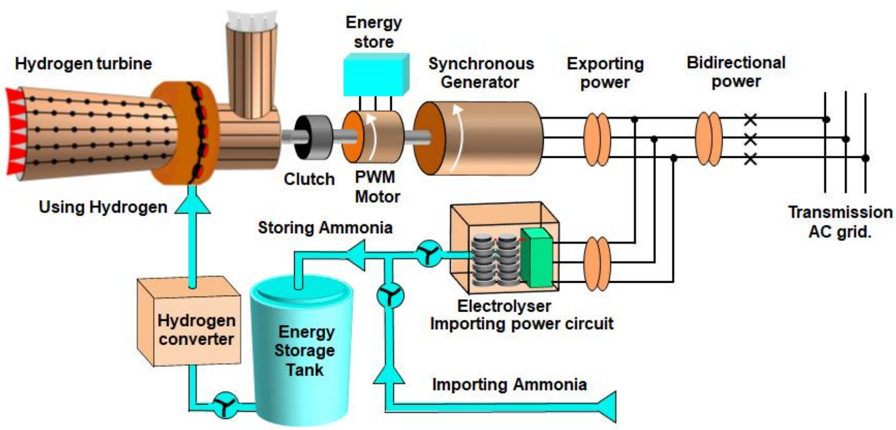


Figure 5.12. The proposed extra power station developments.

The extra abilities shown on **Figure 5.12** are:

- An Electrolyser to produce Ammonia when there is a surplus of the AC Grid's power.
- A **PWM** motor with an Energy store to increase the systems inertia to give an **Optimal SPF unit**.
- An Ammonia to Hydrogen converter so that Hydrogen turbines can be used.

The system an become a self- sustaining system but it still retains the ability to directly import Ammonia from world markets, and the first 2 items can also be added to the **Figure 5.11.**

All AC Grid connected inverter systems will produce a range of harmonic voltage emissions in the range of 500 Hz to over 1 MHz and it is important to have a harmonic emission standard without any gaps in the frequency range. **Enstore** use the IEC 60533 Table 3 emission standard as it has a full frequency range specification.

It is also important for compatibility with the existing AC Grid harmonic filters that inverters only produce odd integer harmonics, as producing either even integer harmonics or inter harmonics can give significant problems. It is also very important that inverters only produce 3^{rd} and triplen harmonics that do not circulate via the AC transformers as certain inverter software can produce circulating 3^{rd} and triplen harmonics.

The harmonic filtering components used by inverters must also be rated for compatibility with the AC Grid harmonic standard to avoid being damaged by inverters with a different **PWM** modulation frequency and they should not produce any significant increase in the impedance of the AC Grid.

The harmonic filtering components used by **GBGF- I** inverters can be omitted from the **standard linear model** shown on **Figure 4.4** as they are not relevant to the low frequency operation of **GBGF** systems.

6. Features not used by GBGF- I inverters in the Linear Operating Mode.

There are several control features that are used by Grid Following **PLL** based inverter that are now allowed in the control system of a **GBGF- I** inverter that provides the **Linear Operating Mode** control which are:

a) The use of a Grid Following **PLL** control, or similar, technology to rapidly alter the phase angle of the **GBGF- I** inverter's **IVS** in response to a change in the **Phase Jump angle** of the AC Grid's supply voltages.

   This technology gives a very high **TIV** plus it also stops the supply of **Active Phase Jump power** which is why it is not allowed in the **Linear Operating Mode** of **GBGF- I** inverters.

b) Existing inverters can use very fast acting control loops to produce a response that looks like an **Active Phase Jump power** response, but this requires very fast changes in the inverter's **IVS** of a **GBGF- I** inverter which are not allowed for **GBGF** compliant inverters.

   This is why the use of **D & Q** fast current loops, or similar, technology to rapidly control the AC supply current of a **GBGF- I** inverters in response to signals in the associated control system is not allowed.

   This technology has produced instabilities in the overall AC Grid system during the operation of existing inverters which is why it is not allowed in the **Linear Operating Mode** of **GBGF- I** inverters.

c) The use of synthetic AC impedances, or similar, technology to alter the effective AC supply impedance of an inverter.

   This alters the effective **TIV** via the action of the control system which is why it is not allowed in the **Linear Operating Mode** of **GBGF- I** inverters as it requires a high bandwidth control.

The control features a) and b) can however be used as part of the **GBGF- I** inverters control system for operating for very short time periods in the **Non-linear Operating Mode**.

7. Operation of the GBGF technology in the Non-linear Operating Mode.

The use of the **standard linear model** of a **GBGF- I** inverter for AC Grid simulation is based on the AC Grid operating within the **NOP** conditions that will be defined in the **NGESO SQSS** document.

Any AC Grid will experience a set of abnormal operating conditions that only occur in either a very small area of the AC Grid or for exceptional conditions.

The most common abnormal operating condition is an AC Grid short circuit fault that only lasts for a short time of 140 ms in GB. The majority of the AC Grid remains in the **NOP** conditions for this type of fault that is cleared by the proven **Grid Fault Ride Through** operating mode of Grid Following inverters.

For this fault it is expected that **GBGF- I** inverters will leave the **Linear Operating Mode** and use the **Grid Fault Ride Through** operating mode for a short time before returning to the **Linear Operating Mode**.

The operation of a specific **GBGF- I** inverter for these abnormal operating conditions are separately simulated for a specific design from a supplier.

A **GBGF- I** inverter's full simulation model for final acceptance by **NGESO** must include the following:

(i) 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.

For this fault condition **GBGF-S** generators are producing reactive power and the large phase angle changes do nor produce damaging mechanical transients.

These large phase angle changes are not relevant for defining the **Maximum Operational Design Limit** for the **Phase Jump angle**.

The required **Fault current profile** is shown on **Figure 7.1** and can use control based on the proven existing Grid Fault Ride Through technology for a short time period before resuming the **Linear Operating Mode.**

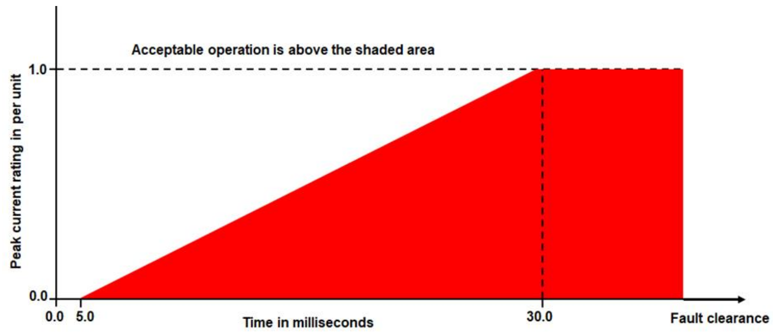


Figure 7.1. Fault current profile.

The required **Minimum reactive current** is shown on **Figure 7.2.**

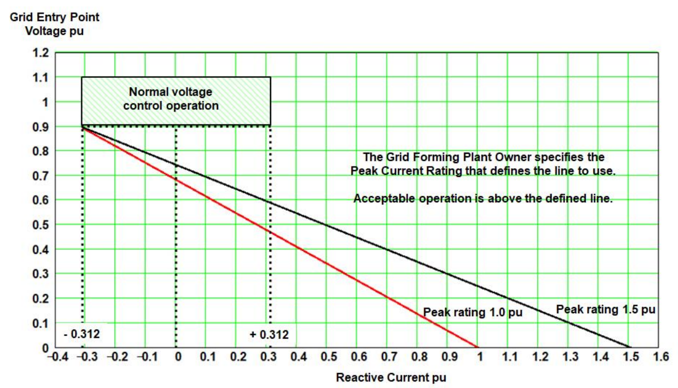


Figure 7.2. Minimum reactive current requirements.

(ii) 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 and is a very rare condition in a very small part of an AC Grid. This large **Phase Jump angle** is not relevant for defining the **Maximum Operational Design Limit** for the **Phase Jump angle**.

This is an existing GB Grid Code requirement and systems only have to remain in operation without tripping for this abnormal operating condition probably using a temporary **PLL** base control.

(iii) Control for **RoCoF 2** rates in the range from 1 Hz / s up to 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.

The provision of this feature in a **GBGF- I** inverter's control is very easy to implement.

(iv) Control and rating validation of the associated energy store form the worst-case transient of 50 Hz to 52Hz then to 47 Hz as defined in **GBGF** Grid Code **Section ECP.A.3.9.4. iv),** see **Figure 7.3.**

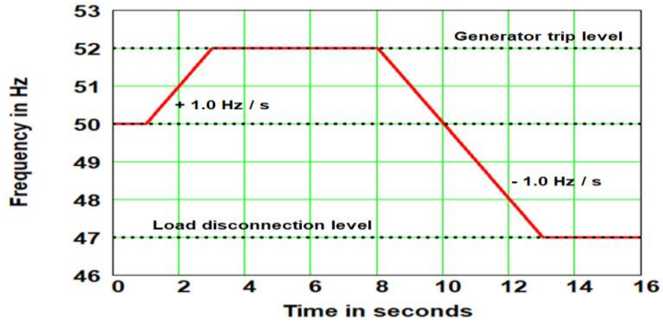


Figure 7.3. Require worst case response.

This is an abnormal operating condition that can arise and is required to ensure that the automatic disconnection systems have time to operate. This condition can be simulated for an AC Grid by using the **standard linear model** and this test is to validate that a supplier has supplied the correct value of the stored energy for a **SPF GBGF- I** inverter.

The required energy storage must deliver approximately 20 % of the energy compared with the stored energy in an equivalent synchronous generator. The required energy store will require a larger value that depends on the system's design which is why the **H** value for a **GBGF- I** inverter cannot be defined by the system's stored energy.

8. Testing and recording systems.

To observe the operation of a **GBGF- I** inverter needs a significant change in the AC Grid that only occurs for significant faults. The **GBGF** Grid code is proposing that a **FIFO** data logging system, or equivalent, is used to capture any major AC Grid transient for analysis at a later date.

The **GBGF- I** inverter also incorporates a test feature to apply a pre-set phase jump in to the inverter's **IVS** voltage. This gives the same power profile as an AC Grid's **Phase Jump angle**. The test can be used as needed to validate that a system is operating correctly during routine site tests, see **Figure 8.1**.

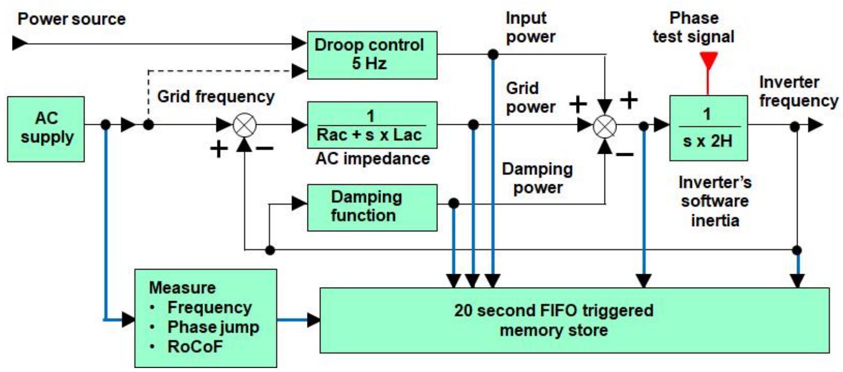


Figure 8.1. Test and Recording systems.

There is a **GBGF** Grid Code 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 significant **Phase Jump angles**.

The **Figure 4.3** shows an instantaneous change in the frequency of the AC Grid which is not possible and the frequency differences are really dynamic phase differences that have caused the frequency errors.

This needs to be eliminated to give accurate results. **Enstore** has extra data on a system to measure the AC Grid's frequency than is not affected by AC Grid's **Phase Jump angle** and also gives a value for the AC Grid's **Phase Jump angle**. For accurate measurement of phase changes requires a system sampling at a rate near to 100 kHz, see **Reference 8**.

9. Data on NFP plots.

When a supplier is starting to develop a **GBGF- I** inverter system it is important that the proposed design provides a viable service to the **NGESO**. This is done by submitting a set of data for the proposed service to the **NGESO** that includes a **NFP** plot and other data which the **NGESO** can either accept or propose changes.

There are a wide range of **NFP** plots that can be defined and the standard **NFP** plot shows the Gain and Phase of a systems AC power / current for low amplitude frequency changes in the AC Grid input as defined in several **ENTSO-E** documents, **see Reference 2**.

The standard **NFP** plot is a key part of this data as it shows in a defined format the main parameters of a proposed system that includes:

- The systems resonant frequency,
- The systems damping.
- The systems impedance to provide an **Active Phase Jump power** ability.

The standard **NFP** plot can be calculated in the time domain by injecting a low amplitude sinewave for a wide range of frequencies to produce the full set of results needed for one **NFP** plot. This analysis method requires a large number of simulations.

The standard **NFP** plot is normally calculated in the frequency domain that gives very rapid results and produces results that assist in the understanding of **NFP** plots for **GBGF- I** systems, **see Reference 7**.

The **Figure 9.1** shows how **NFP** plots are calculated for the **standard linear model** system.

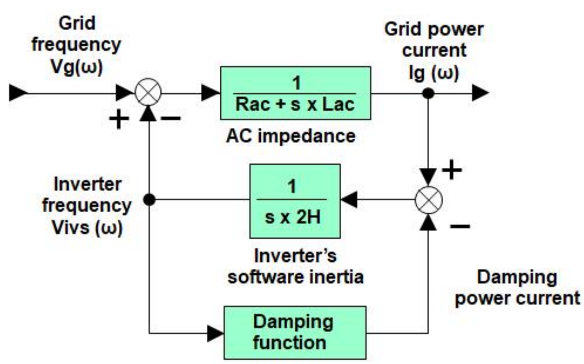


Figure 9.1. Calculating NFP plots.

The input is the AC Grid's frequency and the output is the Grid's power which because the AC voltage is 1 per unit it is the same as the Grid's current change.

Suppliers can use any viable set of circuits and equations to provide this function and validate by comparing results produced from the **standard linear model** system.

The **NFP** plots in the guide have been produced using the **Enstore** damping software function that does have the circuit shown on the **Figure 4.6**.

The **Figure 4.6** is the **standard linear model** system and for a real project many more function blocks would be used to add extra control like either a Power System Stabalising "**PSS**" **control** or a **Droop control** but the core concept is the same.

The same applies to extra function blocks for measurement time delays, the response time of the inverter switching devices and the processor's time delay.

The **Figure 9.2** is an **NFP** plot for a system with:

- **H = 5**.
- An AC supply with a per unit resistance of 0.0025 ohms and a per unit inductance of 0.00106 Henries. This is an AC impedance of 0.333 per unit at 50 Hz that gives a 3 per unit fault current.
- A high level of damping with a resonant frequency of 1.55 Hz.

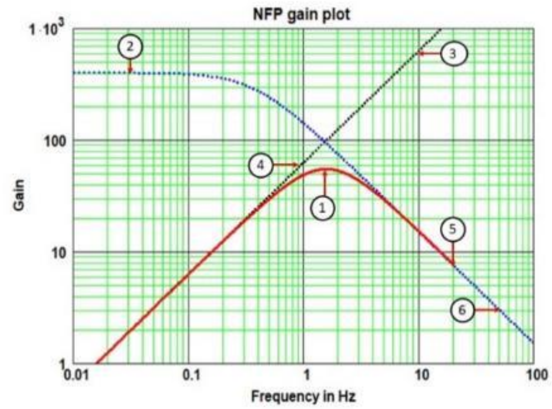


Figure 9.2. Basic NFP plot.

The key features of **Figure 9.2** are:

1. This is the **NFP** plot with a well-defined resonant peak at 1.55 Hz with high damping.
2. This is the admittance of the AC supply function. On **Figure 9.2** at high frequencies the inverter's **IVS** is not changing so this line defines the high frequency part of the **NFP** plot.
3. This is the admittance of the Inertia function. On **Figure 9.2** at low frequencies the inverter's **IVS** has to be at the same frequency AC Grid. This means that the AC current is defined by the input to the software inertia function without damping. This line defines the low frequency part of the **NFP** plot as **Ig(ω) = Vivs(ω) x J x ω** which at low frequencies gives **Ig(ω) = Vg(ω) x J x ω**.
4. At 1 Hz on the line item 3 the admittance of the software inertia is **J x 2 x Pi** = **5 x 2 x Pi** = **62.8**.
5. The **NFP** plot is normally stopped at 20 Hz because the **NFP** plot test input gives unacceptable results at frequencies near to the AC Grid's frequency.
6. At 50 Hz on the line item 6 the admittance of the AC supply = 3.0.

For a full set of data on an **NFP** plot the value of the system's closed loop **Damping Factor** needs to be defined.

The **Damping Factor** value can be calculated, for some **NFP** plots, by a simple equation and a full equation may be produced by the **GFBPW**, see **Reference 7**.

The systems equivalent **Damping Factor** can also be calculated from the **Nichols chart** Open Loop Gain versus Open Loop Phase plot that can be produced as part of producing the system's performance data.

To calculate the equivalent **Damping Factor** the "**Open Loop Phase margin angle**" is measured from the **Nichols chart** for an Open Loop Gain of 1.0. The systems equivalent **Damping Factor** is then calculated from the standard chart, shown on **Figure 9.3** that gives the actual **Damping Factor** from the **Open Loop Phase margin angle** for a standard second order unity feedback system.

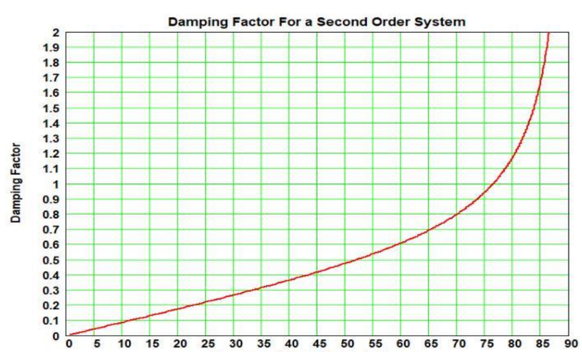


Figure 9.3. Damping Factor graph for a second order system.

The **Figure 9.4** is an **NFP** plot for the data used for **Figure 9.2** plus an extra **NFP** plot with only the damping from the AC supply.

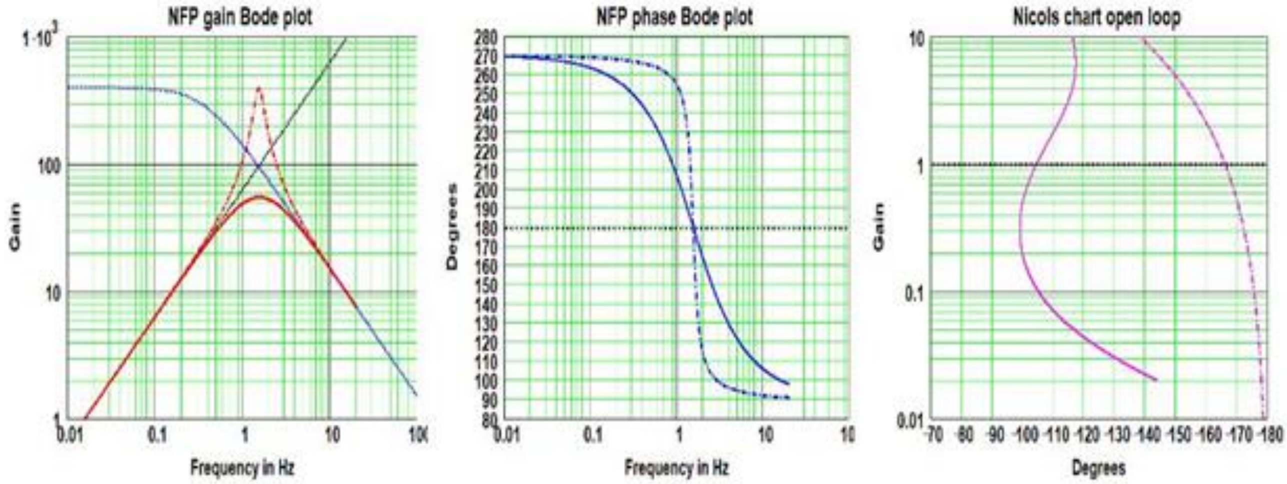


Figure 9.4. Example of an NFP plot plus a Nichols chart all with 2 values of damping.

The **NFP** plot with the solid lines is the data for the **NFP** plot shown on **Figure 9.2** and has:

- An **NFP** plot gain peak of 55 that is produced by the added damping from the damping function.
- An **NFP plot** phase with a slow rate of change of phase at the resonant frequency.
- An impedance at the resonant frequency that is resistive.
- An **NFP** plot phase with a phase shift of 180 degrees at the resonant frequency of 1.55 Hz.
- A **Nichols chart** that gives an **Open Loop Phase margin angle** of 75 degrees.
- An equivalent **Damping Factor** of 0.92 for a second order system by using the **Figure 9.3**.
- A **Nichols chart** with an **Open Loop Phase margin angle** that increases as the gain falls which is not normal for a second order systems. This shape is the result of the software damping function adding extra damping and system stability.

The **NFP** plot with the dotted lines is the data for the **NFP** plot shown on **Figure 9.2** with the added damping set to zero and has:

- An **NFP** plot gain peak of 400 that is produced defined by the damping from the AC supply.
- An **NFP plot** phase with a very fast rate of change of phase at the resonant frequency.
- An impedance at the resonant frequency that is resistive.
- An **NFP** plot phase with a phase shift of 180 degrees at the resonant frequency of 1.55 Hz.
- A **Nichols chart** that gives an **Open Loop Phase margin angle** of 14 degrees.
- An equivalent **Damping Factor** of 0.12 for a second order system by using the **Figure 9.3**.
- A **Nichols chart** with an **Open Loop Phase margin angle** that is a more normal shape for a second order system.
- The resistance of the AC supply has been set to a very low value to produce an **NFP** plot with low damping and this can occur with a low power inverter on a stiff AC supply network.
- This shape of this **NFP** plot is undesirable in an AC system due to the rapid phase changes.

For systems that have extra control function further data is available in the **Enstore's** report on **NFP** plots that shows how the **NFP** plot for more complex systems are produced.

The **Enstore's** report on **NFP** plots also contains the full mathematical equations for **NFP** plots that includes the equation of how the system's **Damping Factor** can be directly calculated from a plot like **Figure 9.2**.

Enstore has also proposed a set of acceptable limits for **NFP** plots as shown on **Figure 9.5**.

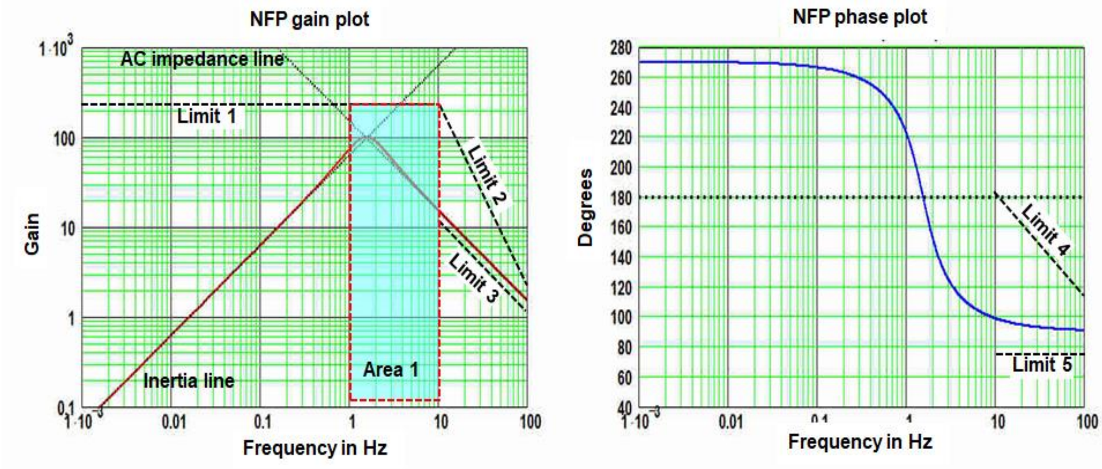


Figure 9.5. Proposed NFP plot limits.

The most important feature of **Figure 9.5** is the **Area 1** that defines the range of allowed **NFP** plot resonant frequencies as 1 to 10 Hz.

With **GBGF- I** inverters it is possible to use very high **H** values that produce very low **NFP** plot frequencies.

The lower 1 Hz frequency limit was chosen to avoid introducing **NFP** plots with very low resonant frequencies that do not presently exist in the AC Grid and if used these systems could adversely interact with the existing **PSS controls** used on **GBGF-S** generator systems.

If a design with a very high **H** value is required there is a design method defined in **Reference 1** that gives the **Active Inertia power** produced that is equivalent to a high **H** value but with acceptable **NFP** plot frequency.

The upper 10 Hz frequency can occur with small systems on a distribution AC Grid and the 10 Hz limit was chosen to ensure that a viable time response for the **Active Phase jump power** that is produced for **Phase Jump angle** transients.

The main item that needs to be finalised by the **GFBPW** is the **Area 1** that defines the acceptable range of **NFP** plot resonant frequencies as the reasons for the five **Limit lines** are now fully defined in the **GFBPW** SharePoint files.

This is important as it is possible that very low **NFP** plot resonant frequencies from **GBGF- I** inverters will not be compatible with the existing GB AC Grid and that very high **NFP** plot resonant frequencies will give an unacceptable **Active Phase Jump power** response.

This is needed so that it is possible to validate that any proposed designs submitted to the **NGESO** are acceptable as **NFP** plot resonant frequencies outside the **Area 1** may not be comparable with the AC Grid.

The **Area1** can be validated by using a system like the **Real-Time Simulation based Grid Forming Modelling** system presented in the latest **GFBPW** meeting by Birmingham University that test a range of **GBGF- I** inverter parameters versus a model of the GB AC Grid.

The **standard linear model** for a **GBGF- I** inverter shown on the **Figure 4.6** is all that is needed to do this work as a **GBGF- I** inverter model with current limiting or other functions is not needed.

The proposed data that is submitted to the **NGESO** at the start of a project is:

- An **NFP** plot for the basic system without extra control functions so that the basic response is defined.
- An **NFP** plot for the full system with the extra control functions so that the full response is defined, see **Figure 9.7**.
- The open loop **Nichols chart** so that the stability of the closed loop function is defined.
- A time domain plot giving the systems AC current for an AC Grid's **Phase Jump angle, see Figure 9.6** for the **NOP** condition limits as shown on **Figure 9.5**. This is to validate that a system is correctly rated to operate in **the Linear Operating Mode**.

  The **Figure 9.6** is for a 20-degree **Phase Jump angle** applied over 20 milliseconds to show the response without DC transient components that occur for immediate phase angle changes.

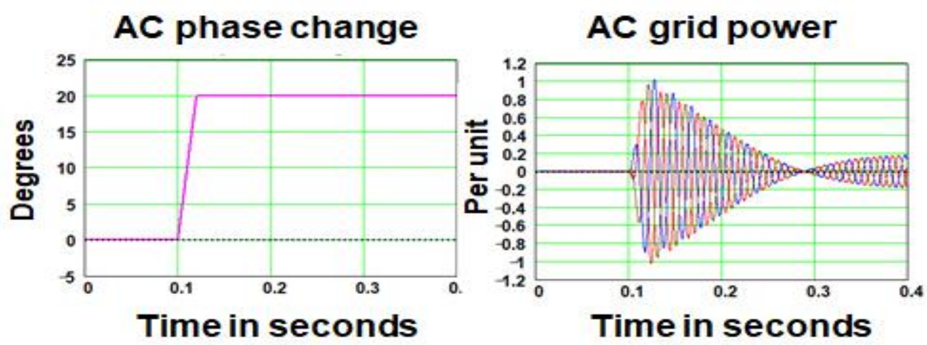


Figure 9.6. Typical AC Phase Jump angle current.

The **Figure 9.7** are the **NFP** plots for a system with low frequency **Droop** control.

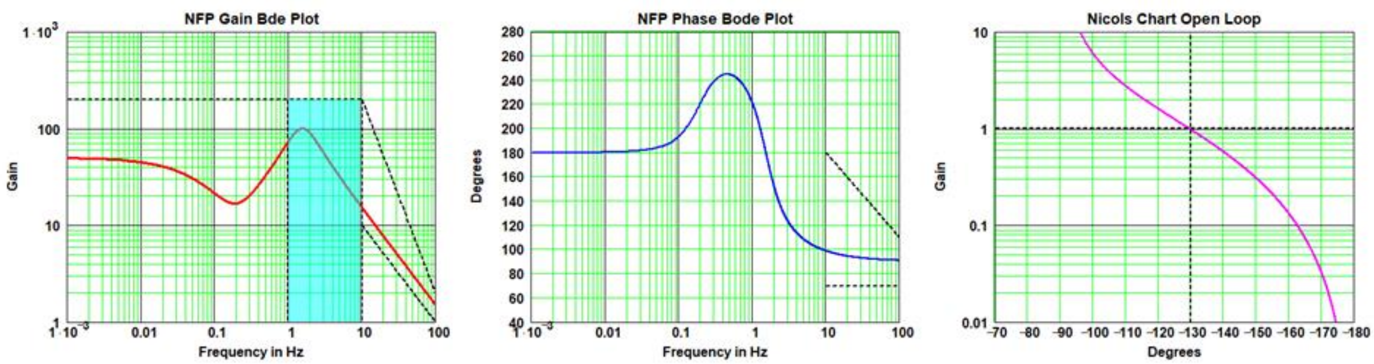


Figure 9.7. Typical AC phase Jump current.

For **GBGF-S** generators the **Active Control power** in the **FSM** is used on selected generators to control the frequency of the AC Grid by using a **Droop gain** function. A typical **Droop gain** is a 100 % power change for a 2 Hz AC Grid's frequency change which is 4 % of 50 Hz. This is a Droop gain of 25.

The **NFP** plot shown on **Figure 9.6** has a low frequency **Droop gain** of 50 that is not affecting the shape of the **NFP** plot in the resonant region. If required **GBGF- I** inverters can use a **Droop gain** at higher frequencies.

Enstore has used the **standard linear model** to calculate real time results like **Figure 9.10** for a **Phase Jump angle** plus a **RoCoF 2** rate.

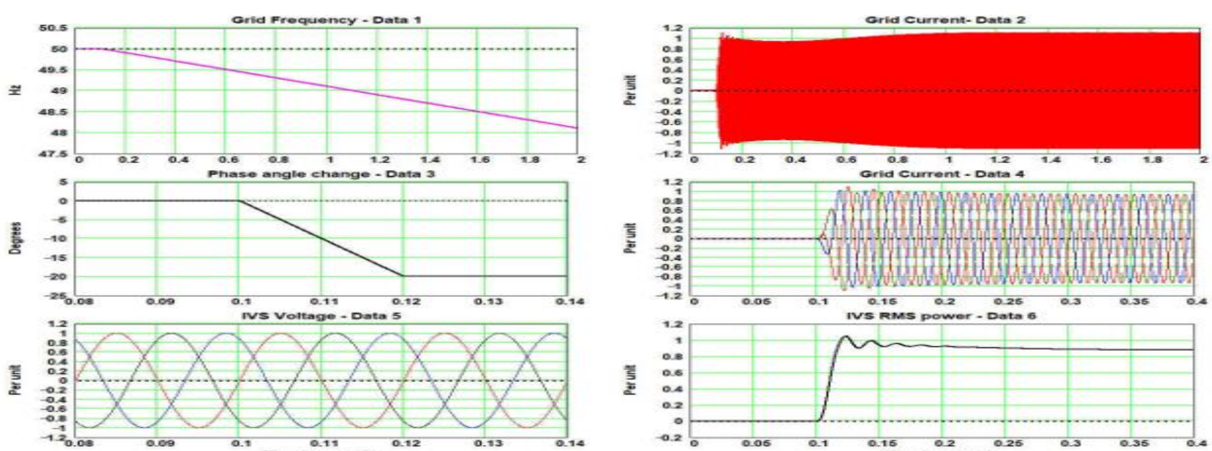


Figure 9.10. Phase Jump angle plus a RoCoF rate linear response.

The **Figure 9.10** is the systems response for a 20-degree **Phase Jump angle** of 20 degrees applied in 20 milliseconds plus a **RoCoF 2** rate of – 1 Hz / s. This is the response of an optimal **SPF GBGF- I** inverter.

10. References

Reference 1.

A Minimum Specification Required for Provision of GB Grid Forming Capability.

https://www.nationalGrideso.com/document/207576/download

This **Enstore's GBGF Guide** can be down loaded by using the link and opening the **Annex 18.**

Reference 2.

High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS) from ENTSO-E

https://consultations.entsoe.eu/system-development/entso-e-connection-codes-implementation-guidance-d-3/user_uploads/igd-high-penetration-of-power-electronic-interfaced-power-sources.pdf

Reference 3.

The Enstore's reply to the BEIS call for evidence – 001BPW.

Data available via either **the GFBPW-** SharePoint files or **Enstore.**

Reference 4.

Peak Current Rating of GBGF Stability Pathfinder systems - Enstore 10 - 004FF

Data available via either **the GFBPW-** SharePoint files or **Enstore.**

Reference 5.

The Enstore's model for GB Grid Forming inverters – 001.

Data available via an agreement with **Enstore.**

Reference 6.

The Enstore's report for TIV analysis, calculating Phase Jump angles and AC Grid design - 001.

Data available via an agreement with **Enstore.**

Reference 7.

The Enstore's report for producing and understanding NFP plots – 001.

Data available via an agreement with **Enstore.**

Reference 8.

The Enstore's report for Phase and frequency sensing – 001.

Data available via an agreement with **Enstore.**

11. Modification record.

Issue	Date	By	Details
001	06/04/2022	**E A Lewis**	• Initial issue.
002	21/04/2022	**E A Lewis**	• Revised based on comments from Antony Johnson the main changes are: • Page 3 for Stage 1 in paragraphs 1, 2 and 6. • Page 3 for Stage 2 in paragraphs 2. • Page 4 in paragraph 2. • Page 4 in Item 6 data added in second part • Page 5 in paragraph 3. • Page 7 in paragraph 1. • Page 7 in paragraph 5 just above Figure 4.3. • Page 18 Section 6 item c. • Page 20 Figure 7.3.