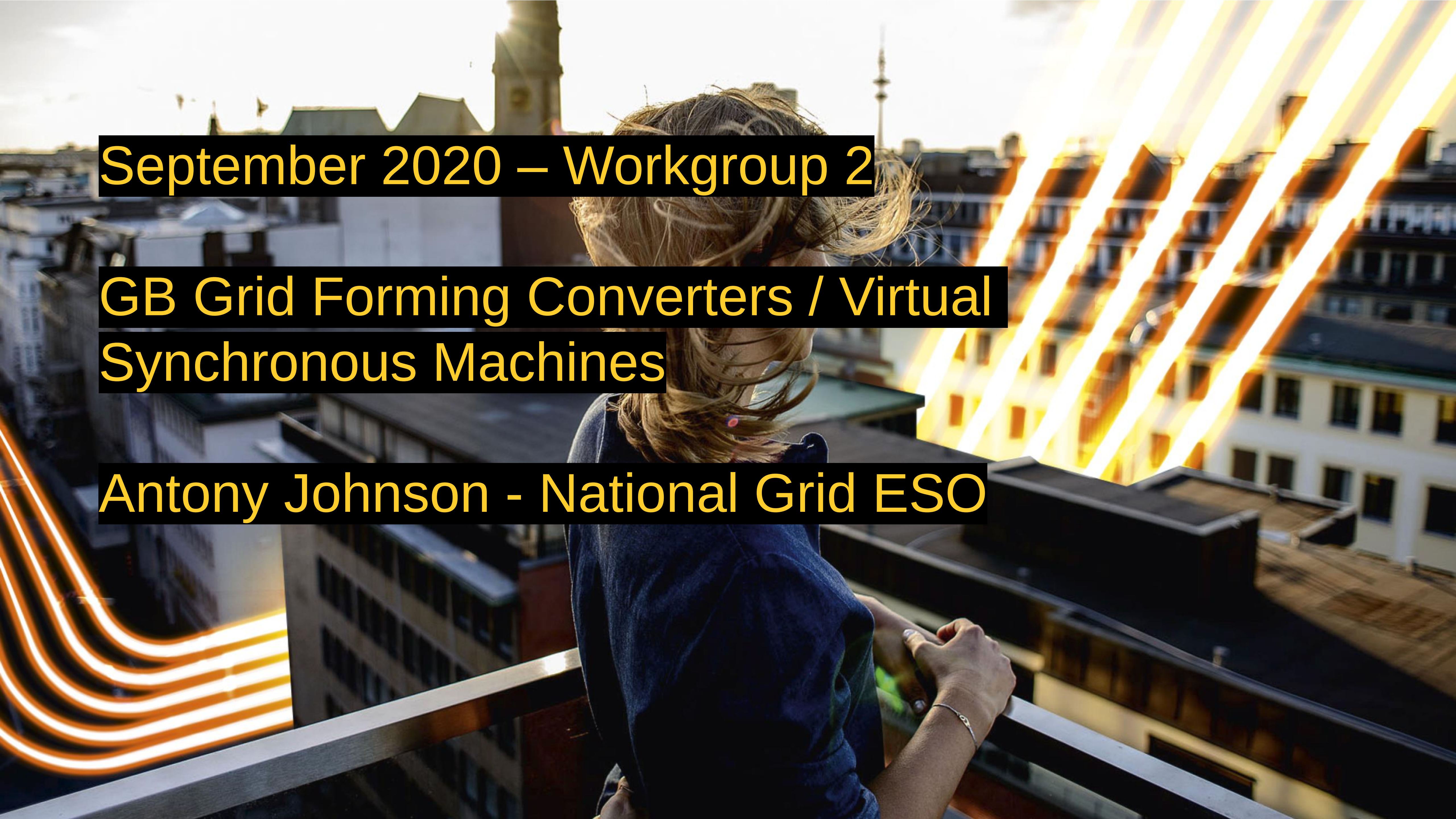


# September 2020 – Workgroup 2

# GB Grid Forming Converters / Virtual Synchronous Machines

Antony Johnson - National Grid ESO

# Summary

- Acknowledgments
- Resume of Synchronous Machine Theory and how this relates to GB Grid Forming
- Synchronous Machines, GB Grid Forming Static Power Converter “**GBGFC**” ( with inertia) , VSM0H ( no inertia) and comparison with current converter based technology
- Grid Forming – Analysis, specification and development
- High Level Grid Code Requirements
- Data Submission and Models
- Compliance Testing and Simulation
- Monitoring
- Determination of System Needs
- Next Steps

# Acknowledgements

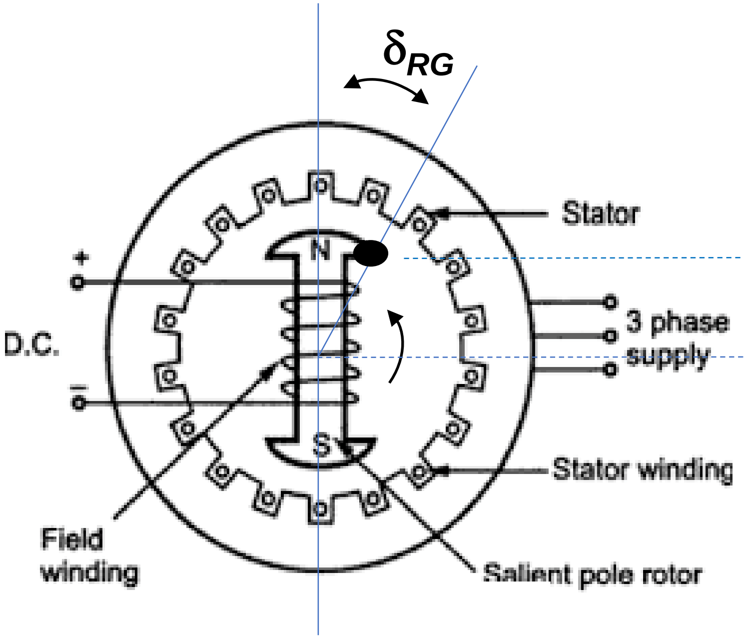
- National Grid ESO would like to thank all those who have provided comments on work presented at the last workgroup in particular Eric Lewis, Mike Kay, Andrew Roscoe and Alastair Frew
- Many of the comments received have been used to develop the next iteration of the specification

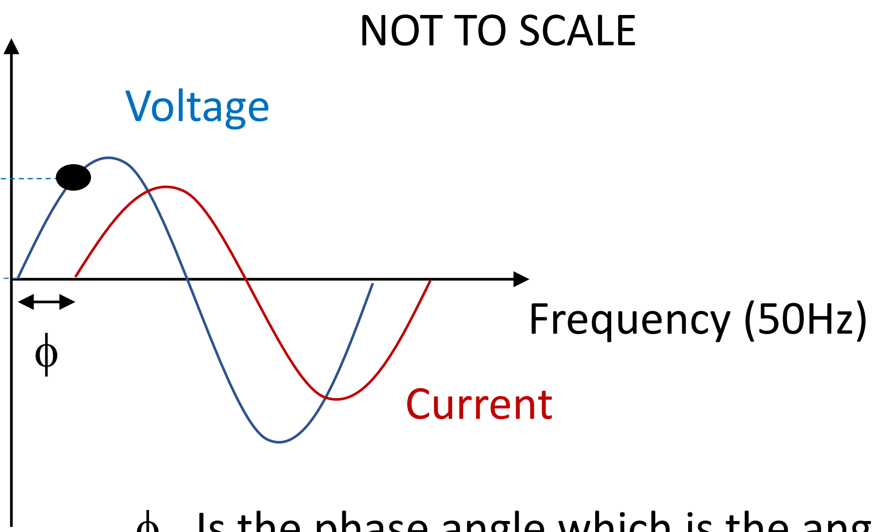
# Key Features

## Key features of GB Grid Forming “ GBGF” technology:

- Applies to compliant GBGF synchronous generators and compliant GBGFC.
- Uses a real internal voltage source “ IVS” behind a real impedance.
- Directly responds in milliseconds to changes in the phase of the AC grid without any actions being required in the associated control system.
- This action produces real phase based Inertia power, real phase based Phase Jump power and real phased based Damping power,
- The control system can respond to changes in external signals but with a Bandwidth below 5 Hz to avoid AC grid resonance problems. This can add extra real control based Damping power if the prime mover has a fast response like GBGFC.
- The control system can respond faster for software signals. e.g. to provide current limits.
- The term Virtual Synchronous Machine “ VSM” is used in many references but many of the proposed designs do not provide these Key features.  Hence it is proposed the term GB Grid Forming is used.

# Resume of the Technology – Synchronous Machines (1)



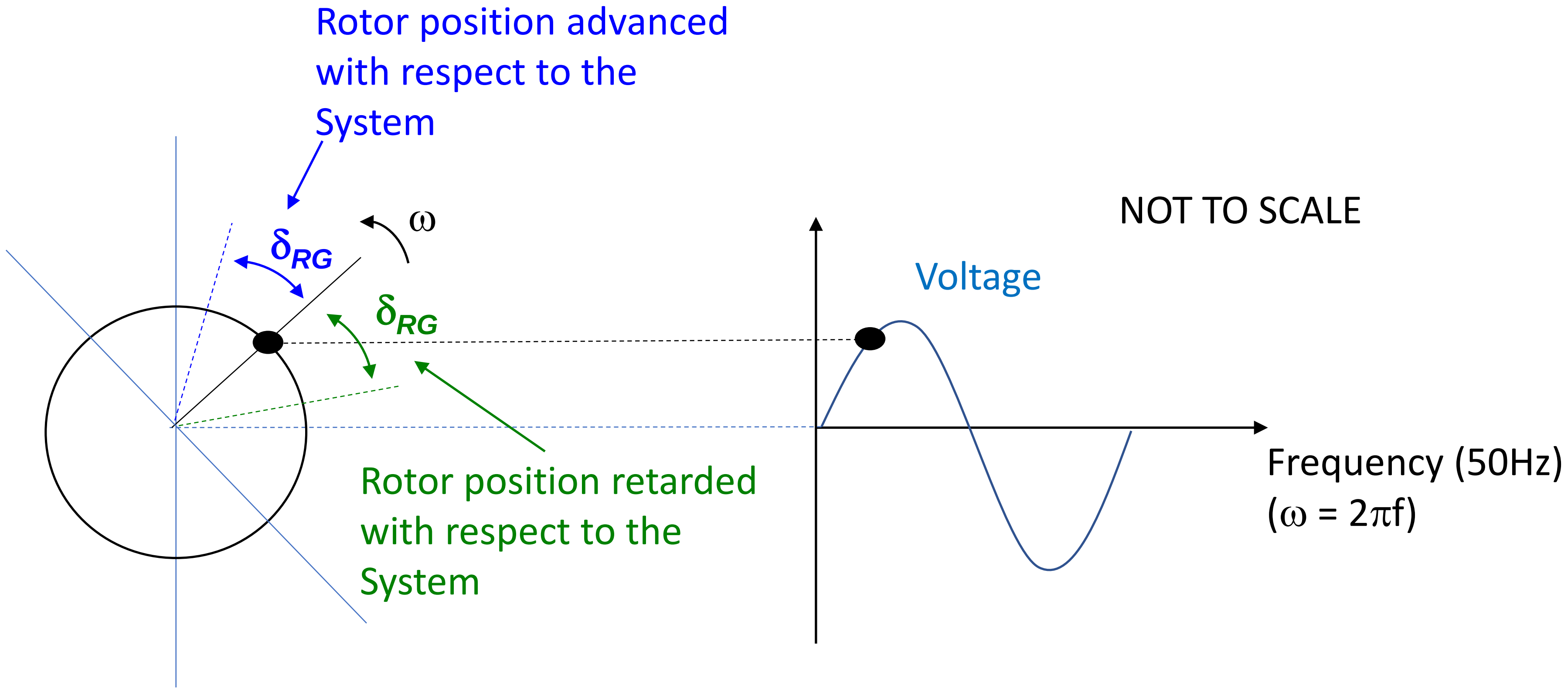


- The rotor has a DC winding which rotates at 3000RPM which for a 2 pole machine is 50 cycles per second or 50 Hz
- This creates a rotating magnetic field so the voltage induced must also fluctuate at 50Hz
- The mechanical rotor is magnetically coupled to the System so there is a direct relationship between the mechanical position of the rotor and the electrical position of the voltage waveform
- The difference between these positions is the load angle $\delta_{RG}$

$\phi$ Is the phase angle which is the angle between Current and voltage. The Power Factor is Cos $\phi$

$\delta_{RG}$ Is the load angle which is the angle between The relative position of the rotor with respect to the System voltage

# Resume of the Technology – Synchronous Machines (2)



Rotor position advanced with respect to the System

$\omega$

$\delta_{RG}$

$\delta_{RG}$

NOT TO SCALE

Voltage

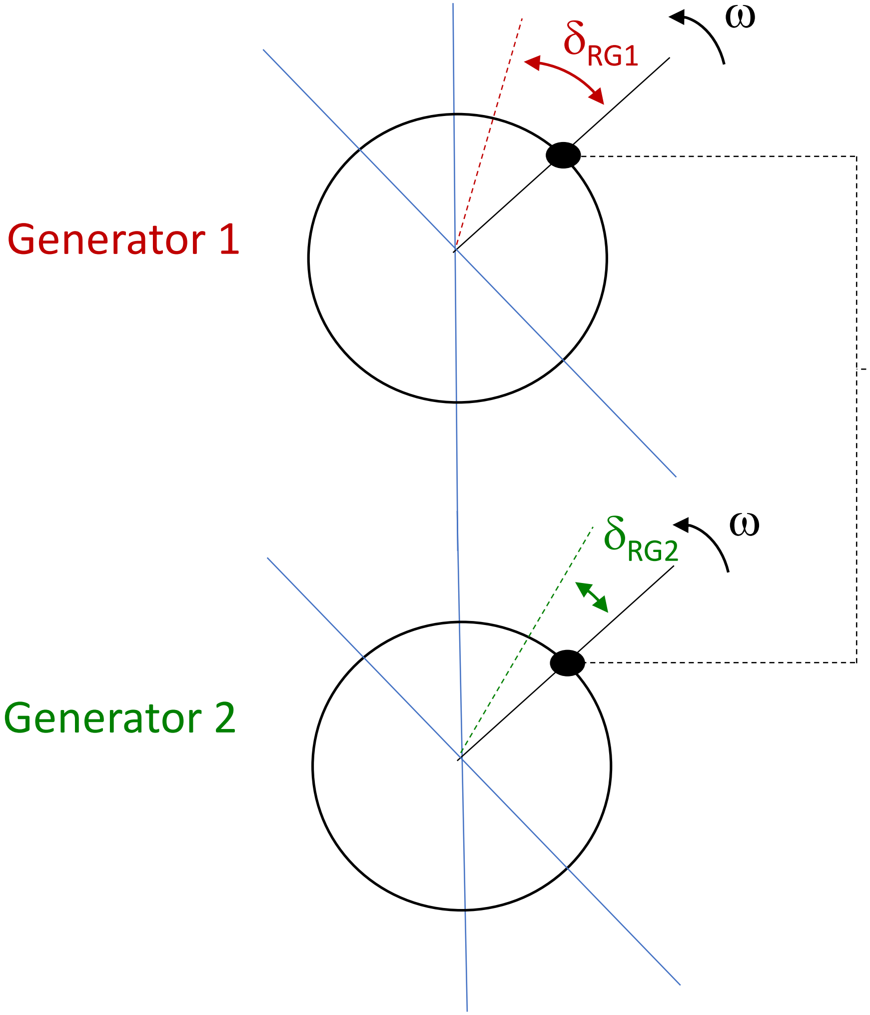
Rotor position retarded with respect to the System

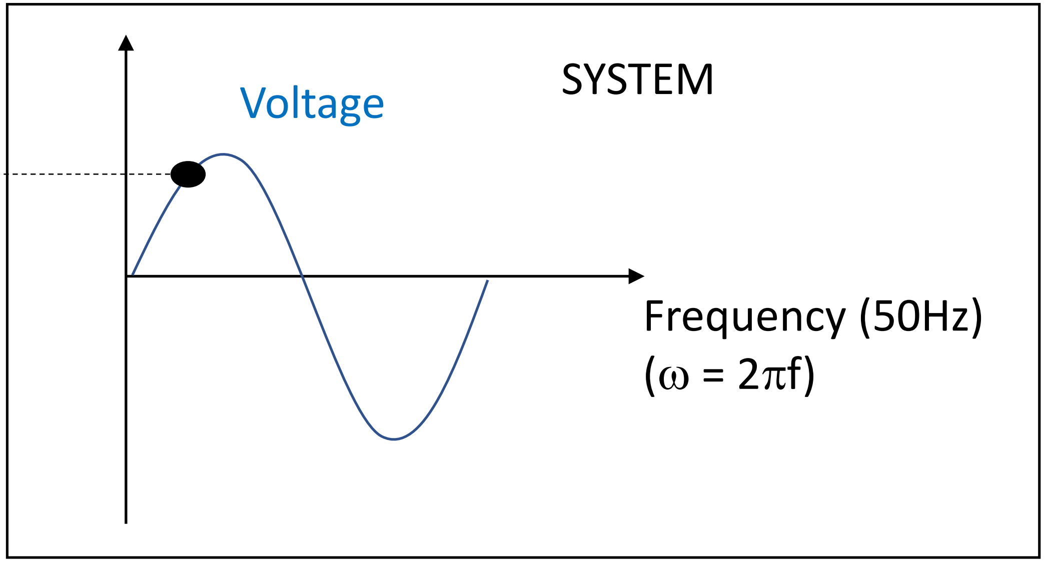
Frequency (50Hz)
($\omega = 2\pi f$)

- Changing the load angle alters the power flow in the AC grid
- The load angle is the relative position between the position of the rotor and the point on the system voltage waveform

# Resume of the Technology – Synchronous Machines (3)

- Each Generator connected to the System will run at the same relative speed, the only difference between them is the load angle as shown by Generator 1 and Generator 2
- This alters the power sharing between generators





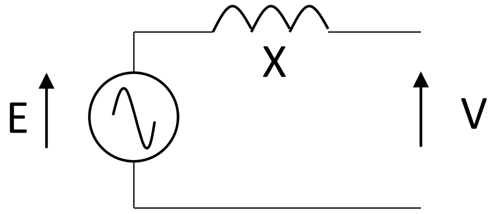
# Synchronous Machines – Features 1

- In a Synchronous Machine the position of the rotor is locked to the system offset by the load angle ($\delta_{RG}$) which can vary by a small amount (90 degrees). The load angle however is operated to prevent pole slipping (ie the machine rotating asynchronously with the system).
- Therefore the rotor must rotate at the same speed as the System and also be in synchronism with the System
- Since the rotor is mechanically coupled to a prime mover – eg a Gas Turbine, Steam Turbine or Hydraulic Turbine any energy released or absorbed by the mechanical rotor must be fed to or from the System.
- It is this rigid coupling which enables inertia (seen as Active Electrical Power) to be transferred to or from the System
- In a system comprising synchronous machines, the rate of fall of system frequency or ROCOF (Rate of change of frequency) is limited by the inertia of the synchronous machines and their drive trains although some types of demand will also contribute to load relief as system frequency falls
- The ROCOF rate for GB Generators (EU Code Users) is set to 1Hz/s. This must not be exceeded to prevent generator tripping but also to facilitate operation of the Low Frequency Demand Disconnection Scheme. Local and National values of ROCOF require careful selection.

# Synchronous Machines – Inertia Power and Phase Jump Power

- The Power developed by a Synchronous Machine is related to the internal voltage source (E)of the machine (via the Exciter), the terminal voltage (V) (both having a magnitude and Phase) the Load Angle (δ) and the Synchronous Reactance (X) as follows.

$$P = \frac{EV}{X} \, Sin \, \delta_{RG}$$

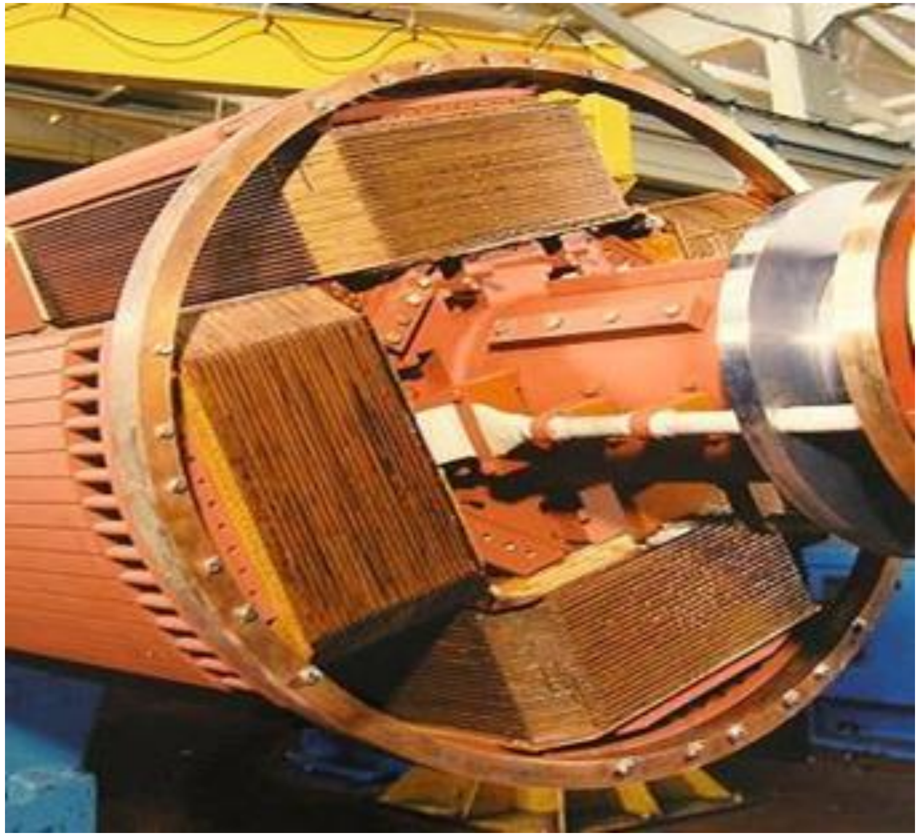


- Hence if is there is a change in the Load Angle there is a change in the power output. Since the rotor has inertia, the speed and hence angular position cannot change instantaneously hence the power cannot change instantaneously.  However Inertia Power will be released or absorbed with respect to the relative position of the rotor to the System
- A change in phase between the voltage on the system (seen at the terminals) and the internal voltage will however result in an instantaneous change in power output.  This is considered to be phase based jump power

# Synchronous Machines – Damping Power and Real Controlled Output Power

- Synchronous machines are fitted with damper windings. These are bars connected to the end winding which behave in the same way as a squirrel cage induction machine. Oscillations on the power system or changes in rotor speed induce a current to flow in the damper winding which has the effect of damping out oscillations on the machine rotor about its equilibrium position
- In the event of a disturbance, a synchronous machine will therefore also produce a temporary change in output power which is referred to as Damping Power.
- Real Controlled Output Power is the steady state power output developed by the generator. The mechanical input power is a product of the torque and speed and the electrical output power is a product of the internal voltage source "IVS", the terminal voltage the sine of the load angle divided by the synchronous reactance.
- An increase in Active Power output can be achieved by opening the governor valve which has the impact of increasing the EMF of the Generator.

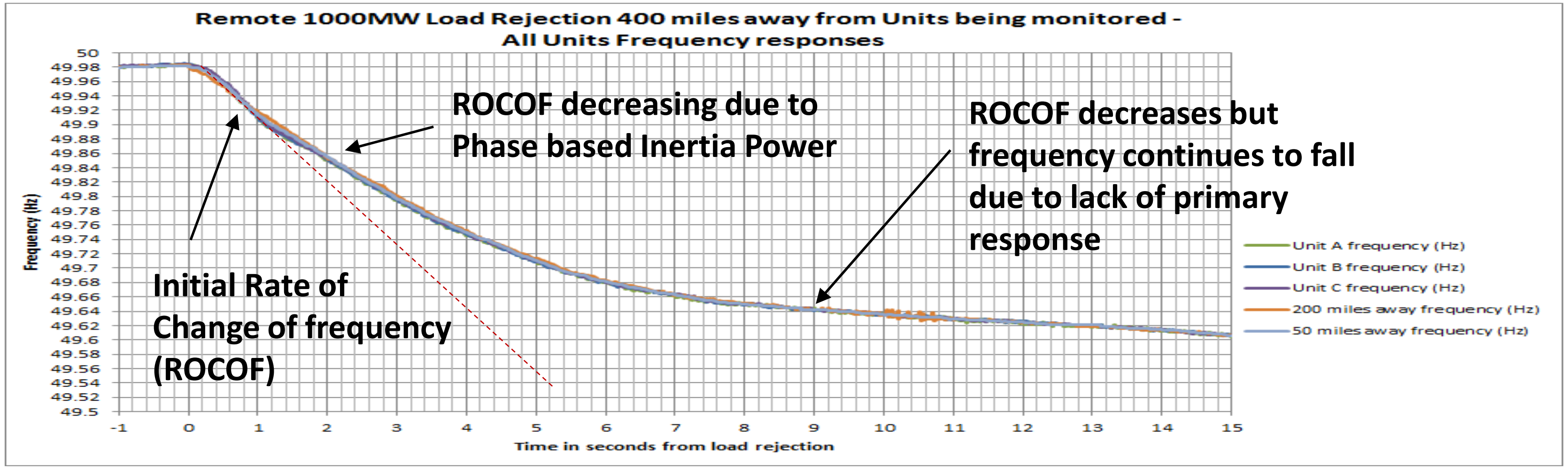
# Synchronous Machine - Damper Windings



# Components of Power injected from a Synchronous Machine

- Phase Based Real Inertia Power
  - P1 $= \frac{EV}{X} \sin \delta_{RG}$ for ramp changes in $\delta_{RG}$
- Phase Based Real Phase Jump Power
  - P2 $= \frac{EV}{X} \sin \delta_{RG}$ for sudden changes in $\delta_{RG}$
- Phase Based Real Damping Power
  - P3 $= \frac{EV}{X} \sin \delta_{RG}$ for the ROCOF changes in $\delta_{RG}$
- Controlled Based real Controlled Output Power
  - $P_M = T\omega \; and \; p \; \frac{EV}{X} sin \, \delta_{RG}$ for slow changes via the control system
- This is why P1 to P3 are called phase based power
- The important point is that the cumulative effective of the injection of active power to the system from the above components act with each other in phase to contribute to the overall performance of the System. This co-ordinated response does not occur in a classical PLL based power electronic converter.

# Example – Remote 1000MW Load Rejection

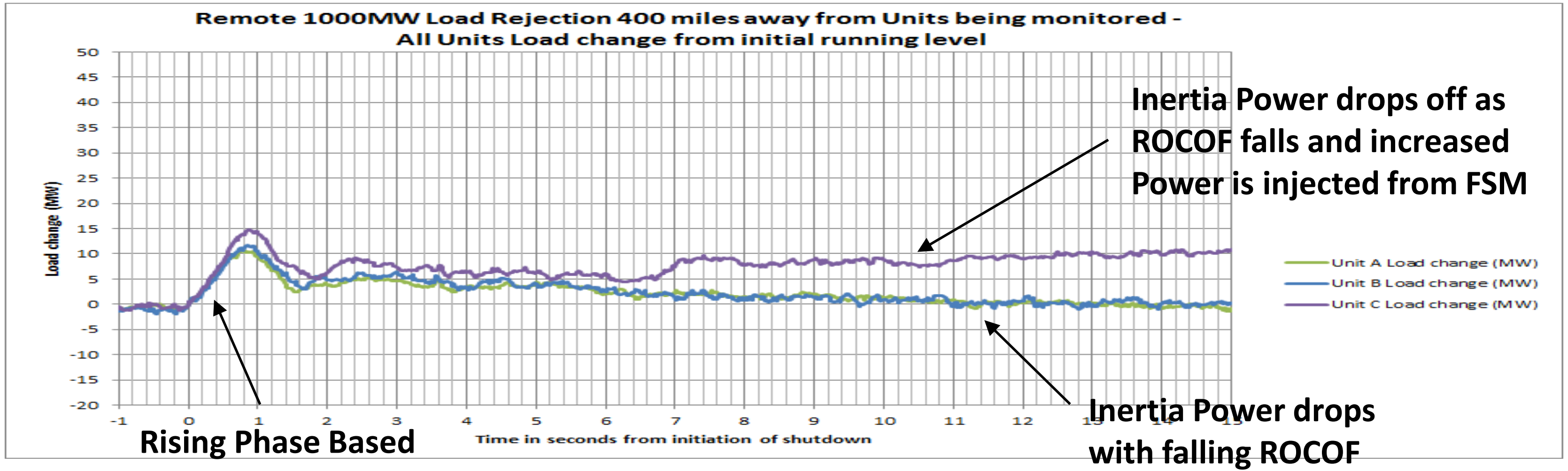


Remote 1000MW Load Rejection 400 miles away from Units being monitored - All Units Frequency responses

ROCOF decreasing due to Phase based Inertia Power

ROCOF decreases but frequency continues to fall due to lack of primary response

Initial Rate of Change of frequency (ROCOF)



Remote 1000MW Load Rejection 400 miles away from Units being monitored - All Units Load change from initial running level

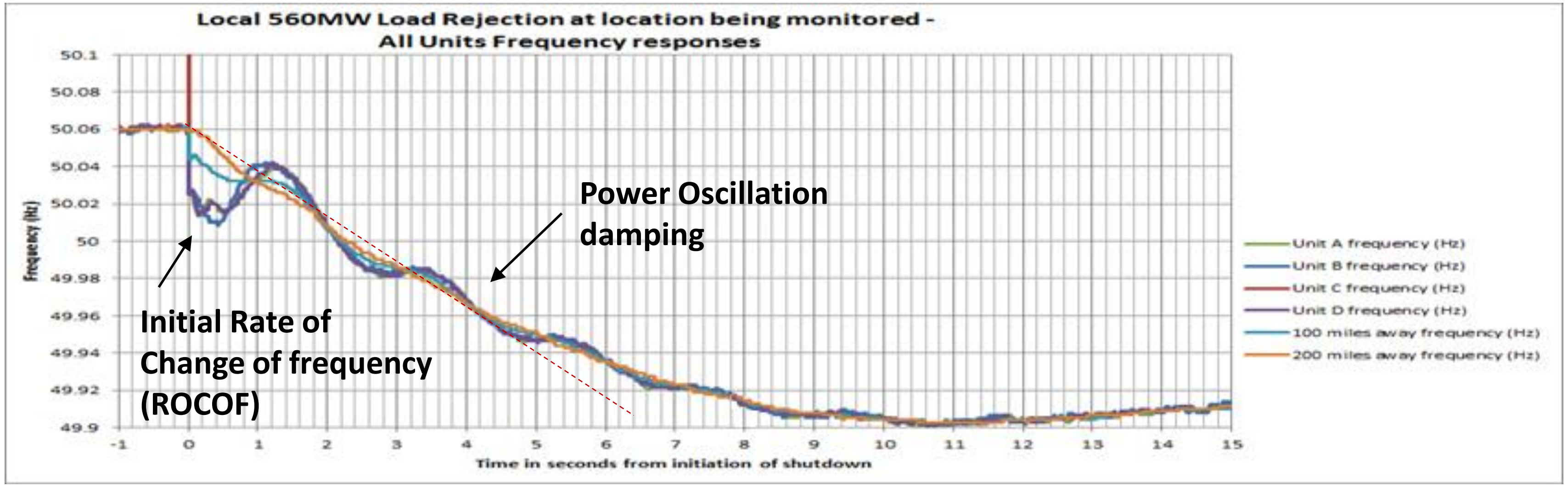
Inertia Power drops off as ROCOF falls and increased Power is injected from FSM

Inertia Power drops with falling ROCOF

Rising Phase Based Inertia Power as the Rotor angle starts to change

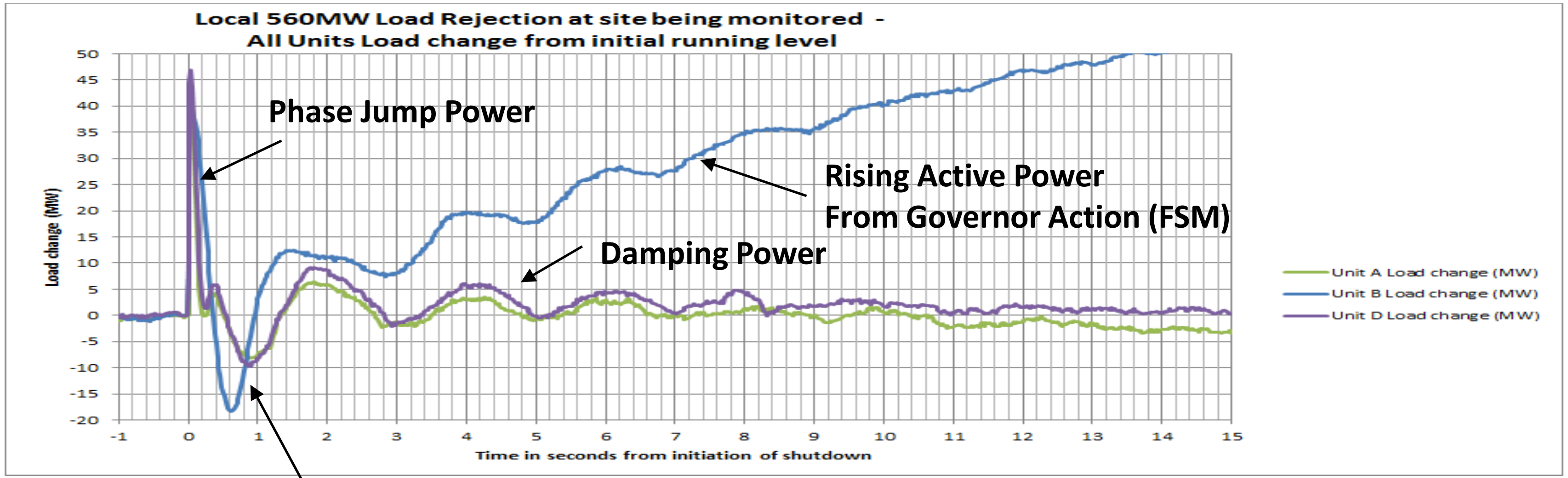
Graphs kindly supplied by Drax

# Example – Remote 560MW Load Rejection


Local 560MW Load Rejection at location being monitored - All Units Frequency responses

Power Oscillation damping

Initial Rate of Change of frequency (ROCOF)


Local 560MW Load Rejection at site being monitored - All Units Load change from initial running level

Phase Jump Power

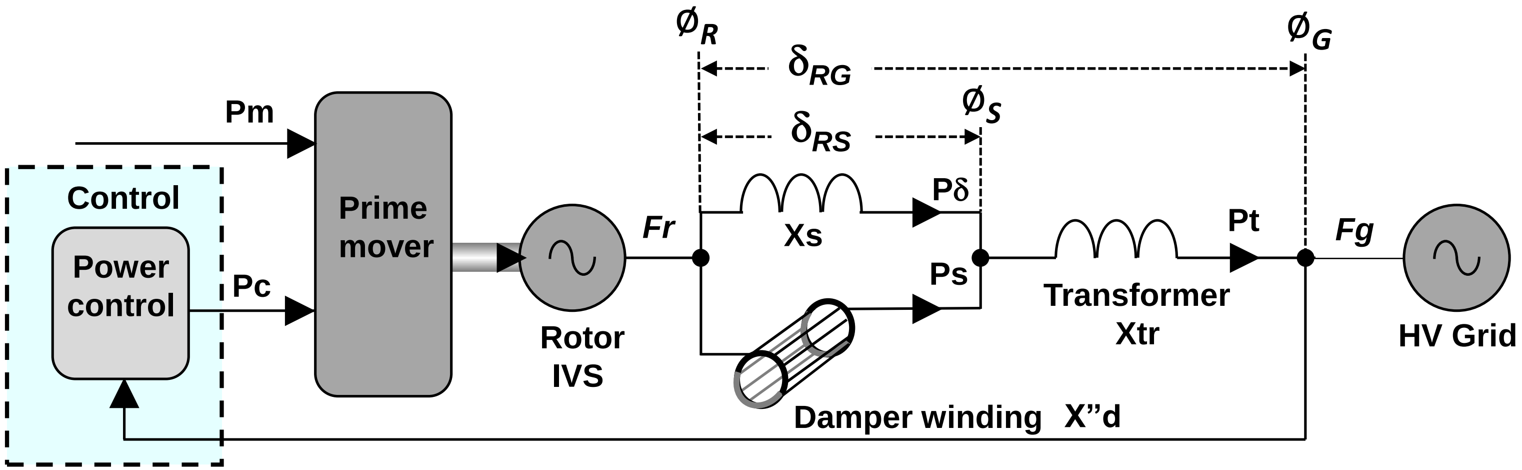
Rising Active Power From Governor Action (FSM)

Damping Power

Inertia power transient of reverse polarity as frequency rises

Graphs kindly supplied by Drax

# Synchronous Machine - Equivalent Circuit Model

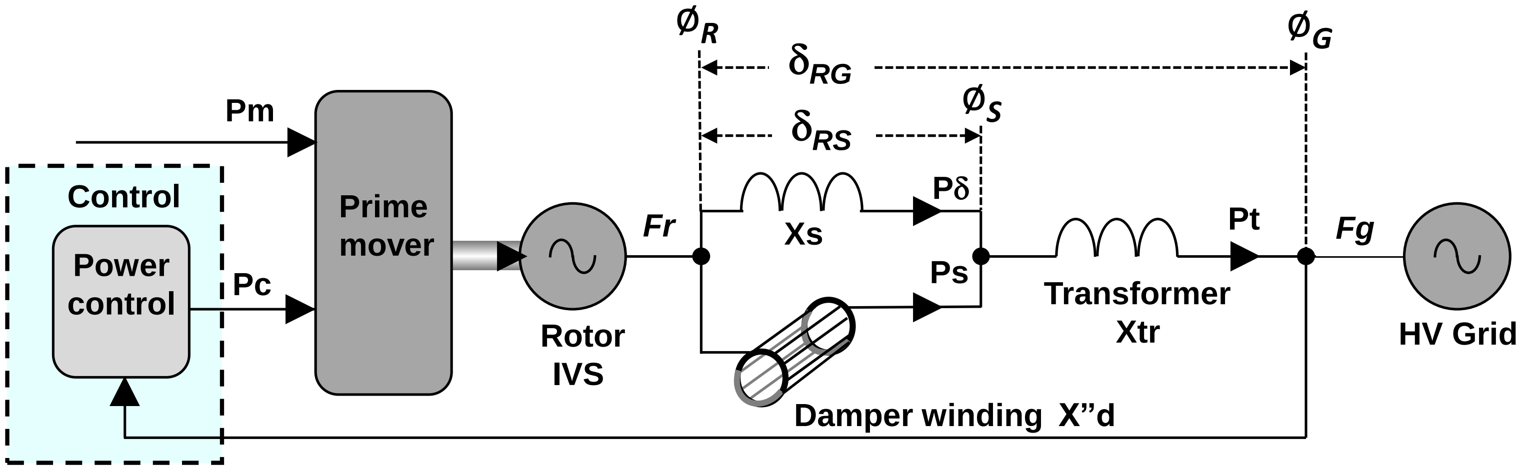


This shows that there are 3 Types of real damping power:

- Via stator winding **Pδ**.
- Via damper windings Ps
- Via slow control Pc

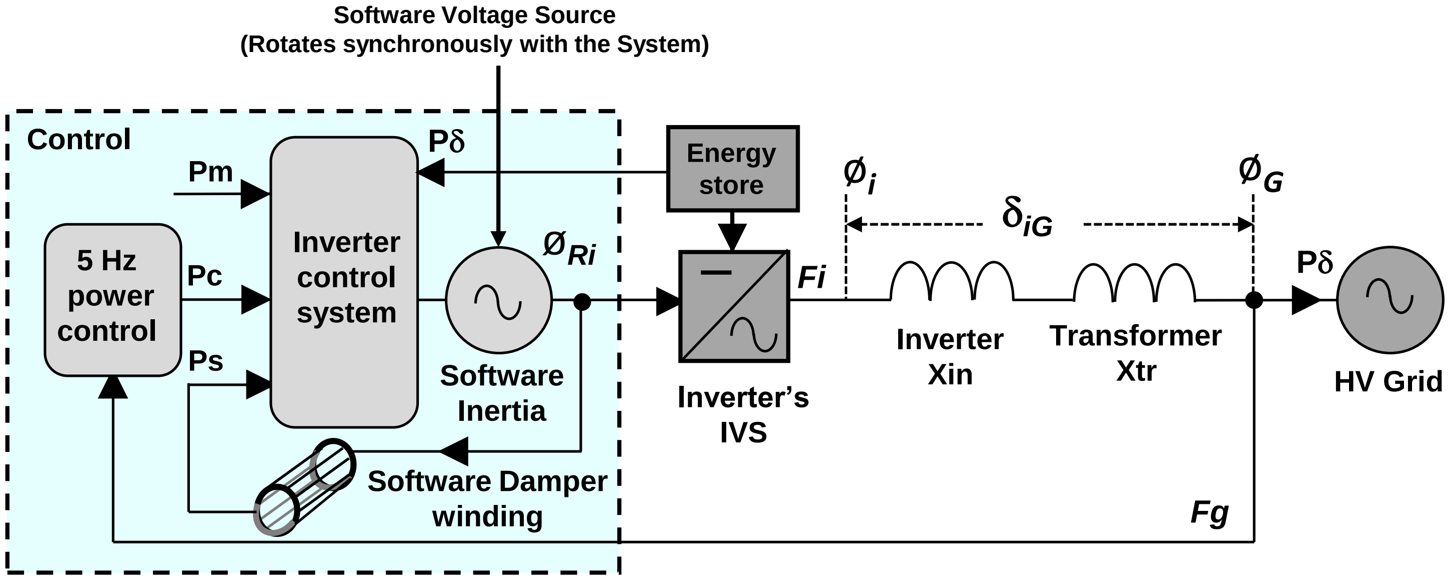
Diagram kindly supplied Enstore Based on data from Andrew Roscoe

# Comparison of a Synchronous Machine and a GBGFC – Equivalent Circuit Models



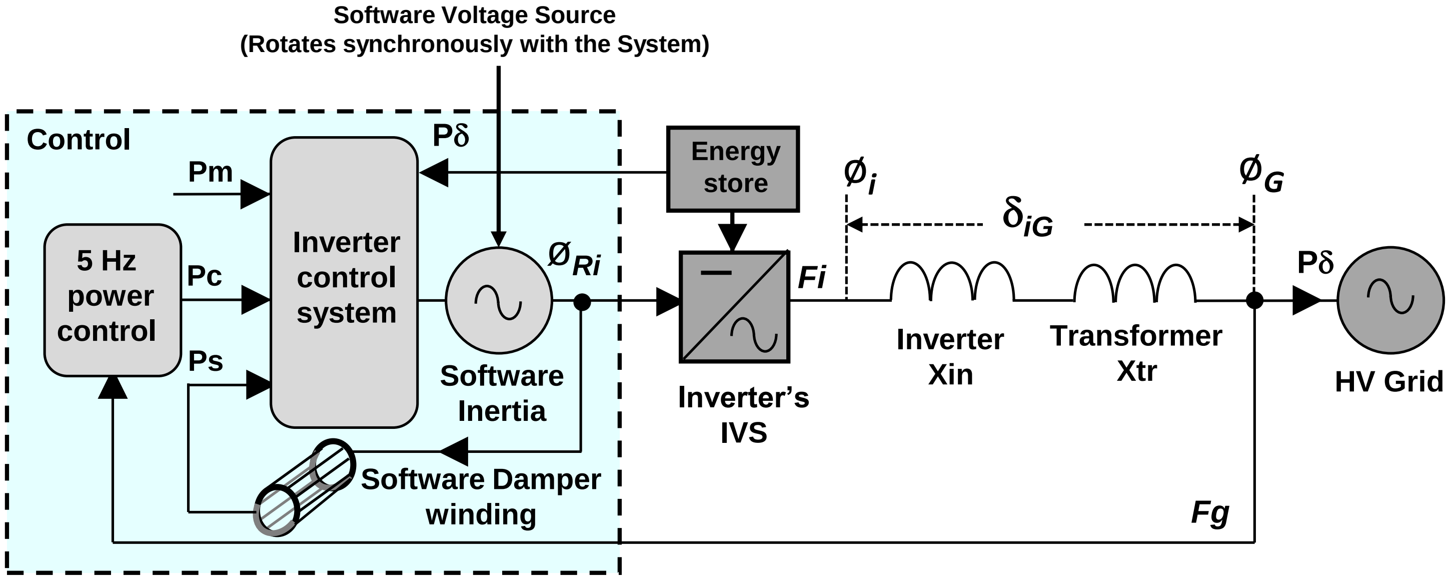
GB Grid Forming
Synchronous Machine

Diagrams adapted from those kindly supplied Enstore and Andrew Roscoe



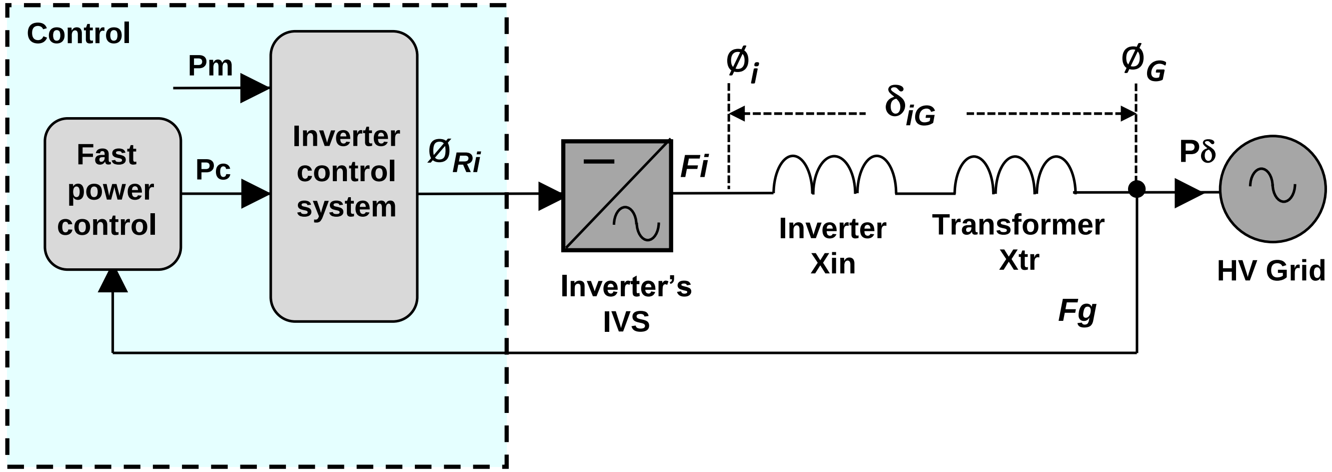
GB Grid Forming
Static Power Converter
(with Inertia)

# Comparison of a GB With Forming with Inertia and VSM0H – Equivalent Circuit



GBGF with software inertia and software damping

Diagrams adapted from those kindly supplied Enstore and Andrew Roscoe



VSM0H without software inertia (no energy store) and without software damping. This requires high bandwidth control to add damping and a response to look like inertia

# Comparison of Synchronous Machine, GBGFC, VSM0H and Current Converter Technology

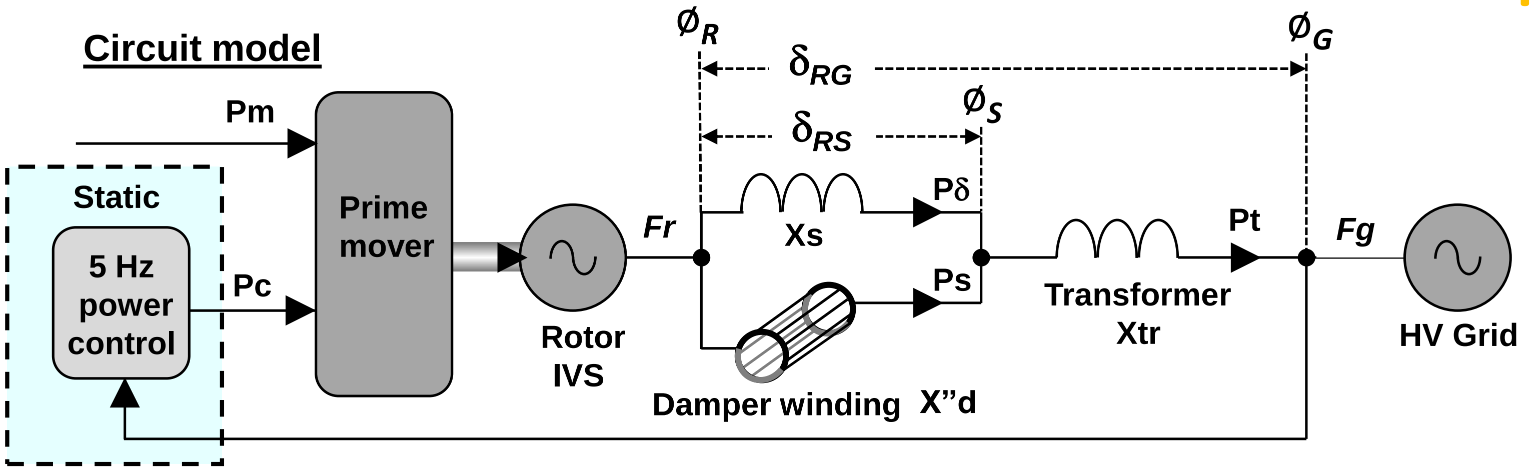
| Capability | Synchronous Machine | GBGFC | VSM0H | Conventional Converter |
|---|---|---|---|---|
| Phased Based Inertia Power | Yes | Yes | Limited | No |
| Phased Based Phase Jump Power | Yes | Yes | Yes | No |
| Damping Power | Yes | Yes | Yes | Yes |
| Response (within one cycle) | Yes | Yes | Yes | No |
| Operate in Synchronism with the System | Yes | Yes | Yes | No |
| Contribution to Fault infeed | Yes - High | Yes | Yes | Limited/slow |
| Bandwidth of control system | Below 5 Hz | Below 5 Hz | Faster than 5 Hz | Faster than 5 HZ |

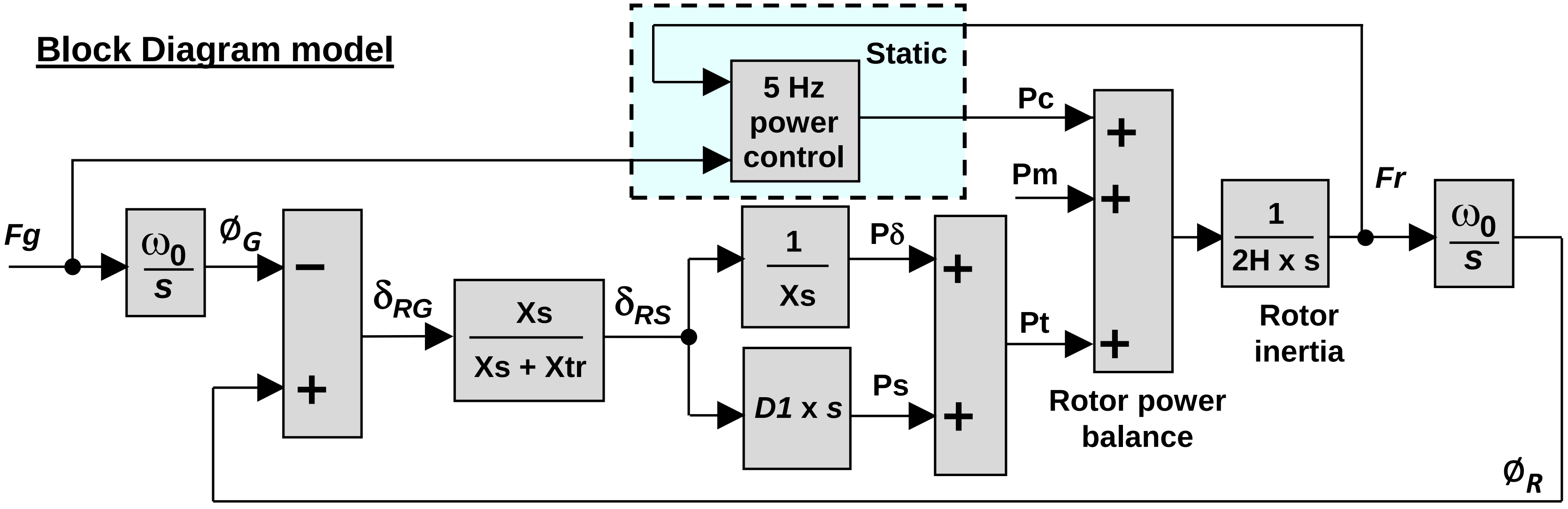
- It is these deficiencies that make VSM0H unsuitable for GB Grid Forming but they do have a place for supporting the Grid during system disturbances even though they do not contribute to inertia
- It is these deficiencies, in particular lack of injected active power and reactive power that will lead to Power System stability issues particularly under disturbed conditions

# Grid Forming – Analysis and Specification Development

- In order to develop a specification we need to undertake some analysis.  The high level steps used in this process are as follows:-
    - Take the equivalent circuit model (see slide 15)
    - Represent this in block diagram format
    - Develop the Closed Loop Transfer Function in the form of the second order characteristic equation
    - Develop Network Frequency Perturbation Plot (Bode Plot)to determine operating characteristics of plant
    - In addition there is also the requirement to run simulation and tests – see slides 32 - 40

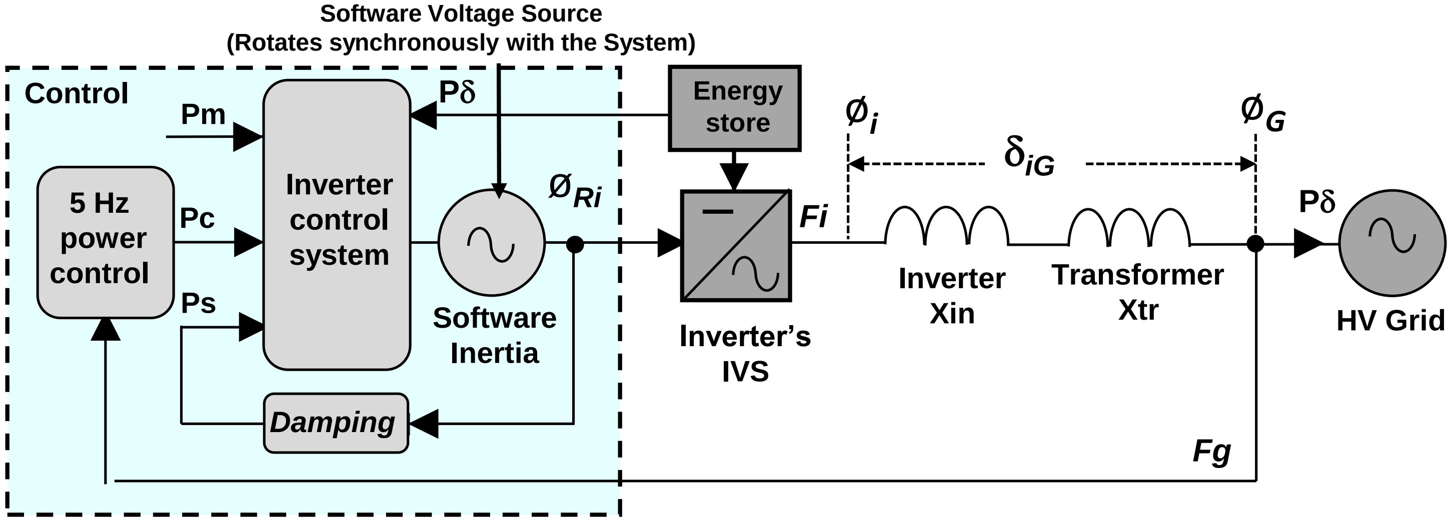
# Equivalent Circuit and Block Diagram Representation of a Synchronous Generator with External Damping


**Circuit model**


**Block Diagram model**

Diagrams developed and supplied by Enstore and Andrew Roscoe

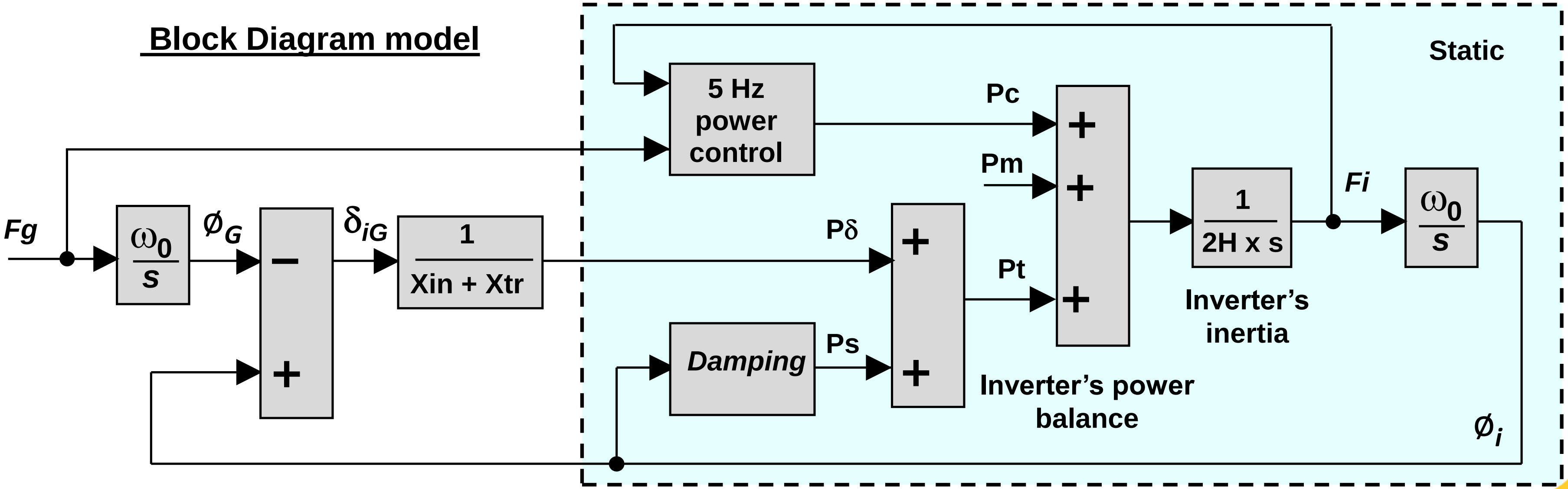
# Equivalent Circuit and Block Diagram of a Grid Forming Static Power Converter with Software Damping



Diagrams developed and supplied by Enstore

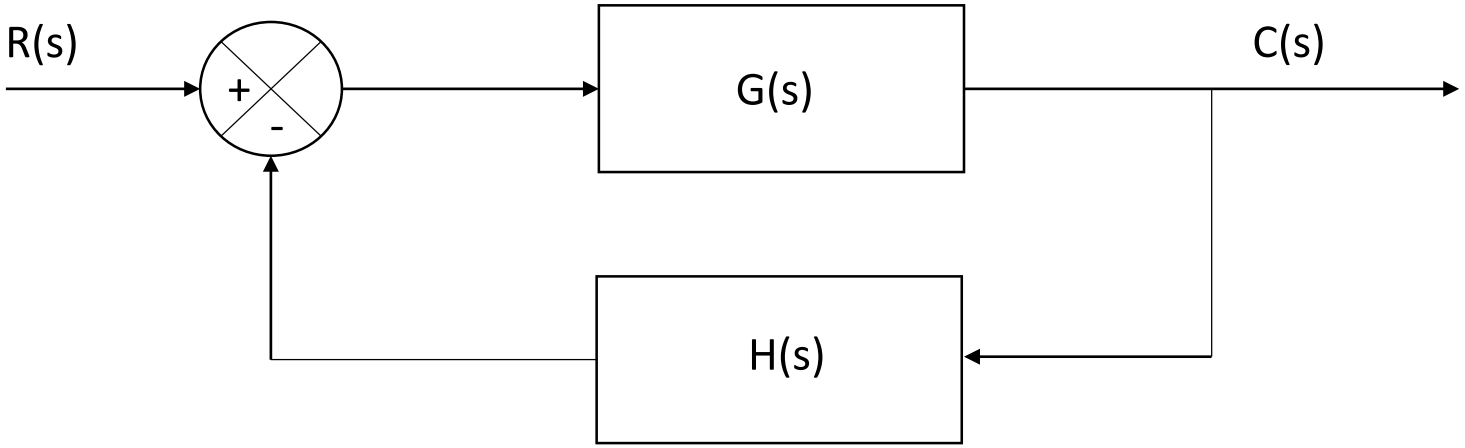
There are now three Damping loops via Ps, Pc and Pδ
That alter the observed damping

## Block Diagram model



# Analysis – Closed Loop Transfer Function

- A typical control system can be represented as follows:-



- The second order Closed Loop transfer function can be taken as:-

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s) \times H(s)} = \frac{\omega_n^{2}}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (1)$$

# Analysis – Closed Loop Transfer Function

- By taking the inverse Laplace Transform of this second order characteristic equation (Equation 1 – slide 22) we can obtain some very useful information

$$\text{The Rise Time}\; t_r = \frac{1}{\omega_d}\tan^{-1}\left(\frac{\omega_d}{-\sigma}\right) = \frac{\pi-\beta}{\omega_d}$$

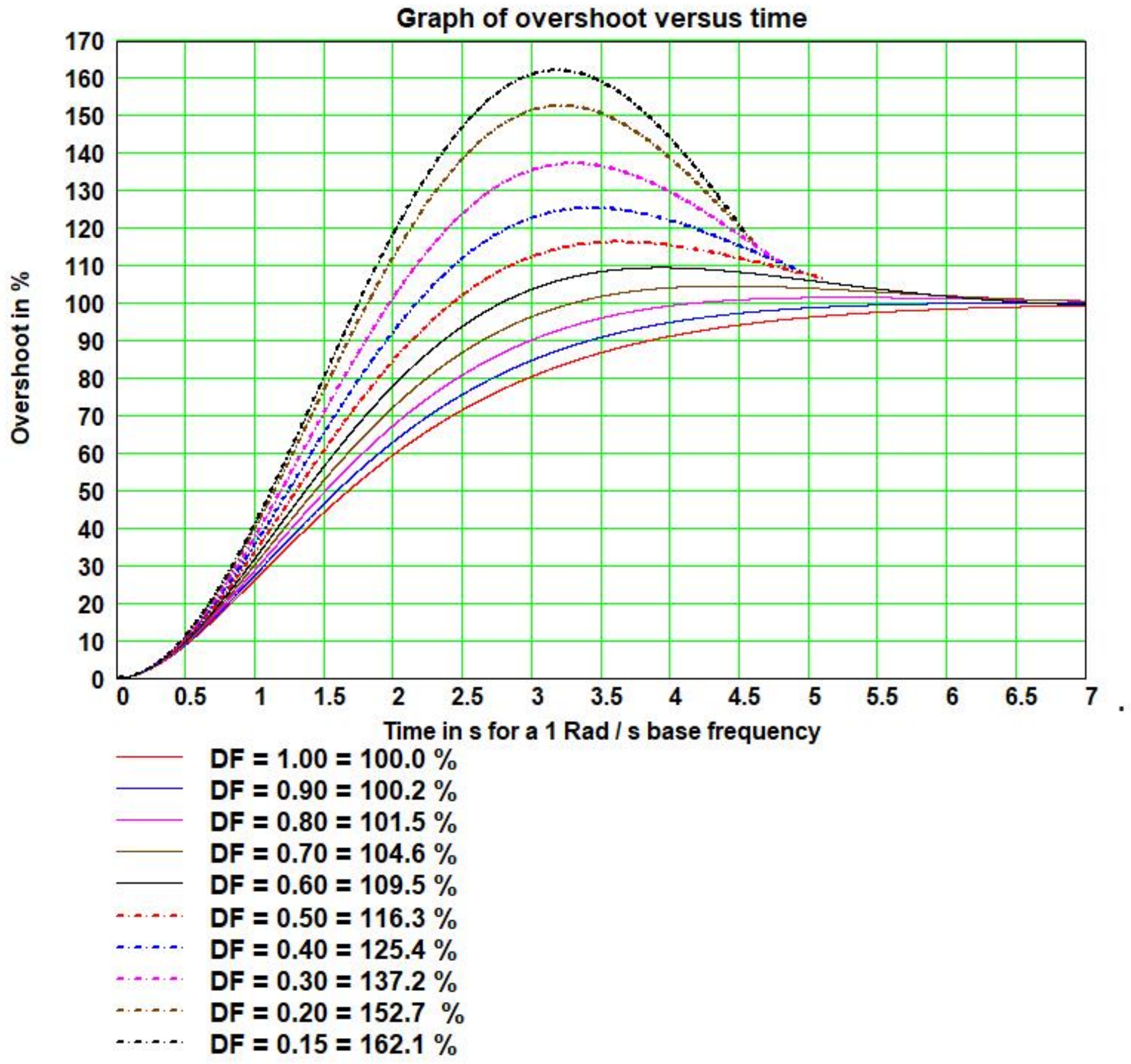
$$\text{Time to first peak overshoot}\; t_r = \frac{\pi}{\omega_d}$$

$$\text{The Maximum Overshoot}\; M_p = e^{-(\varsigma/\sqrt{1-\varsigma^2})\pi}$$

$$\text{The settling time}\; t_s = 1 - \frac{e-\zeta\omega_n t}{\sqrt{1-\zeta^2}}\sin(\omega_d t + \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta})$$

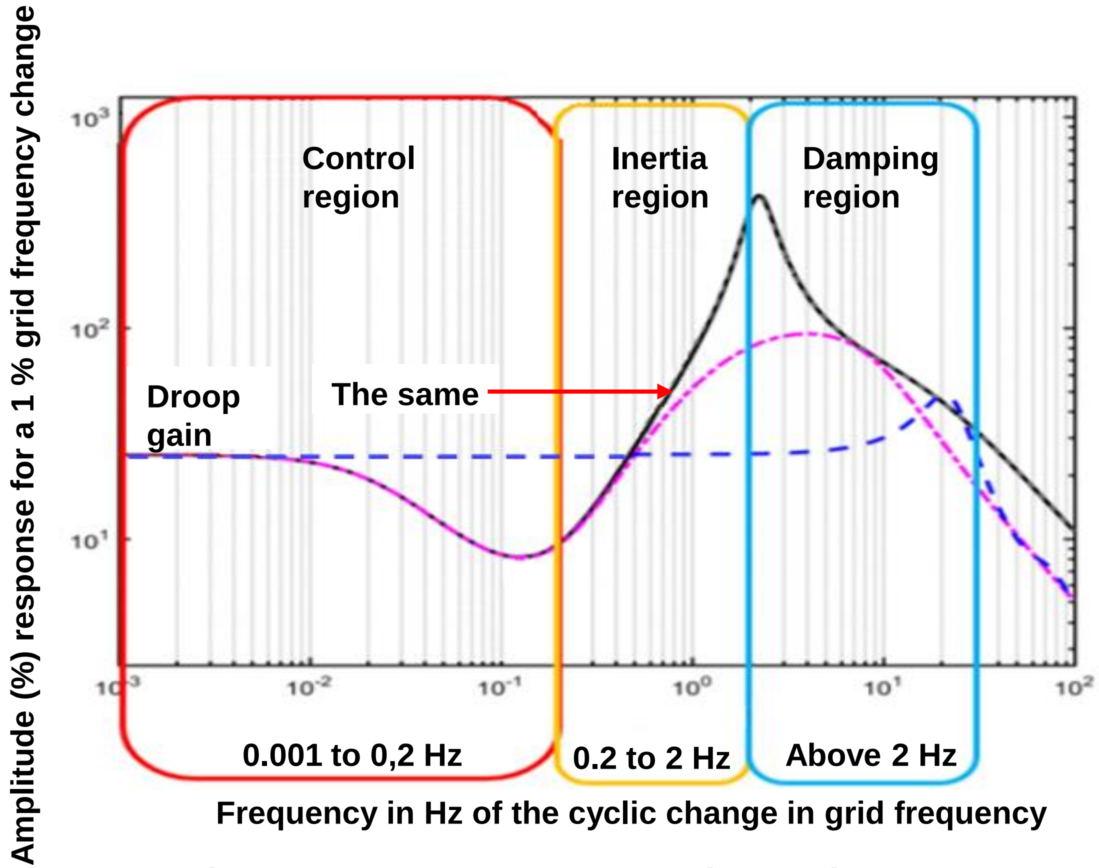
- These are important and they give important characteristics as to how the System should be designed. The term ζ is important here as it defines the Damping Ratio also called the Damping Factor.
- This is how the Damping Factor can be measured

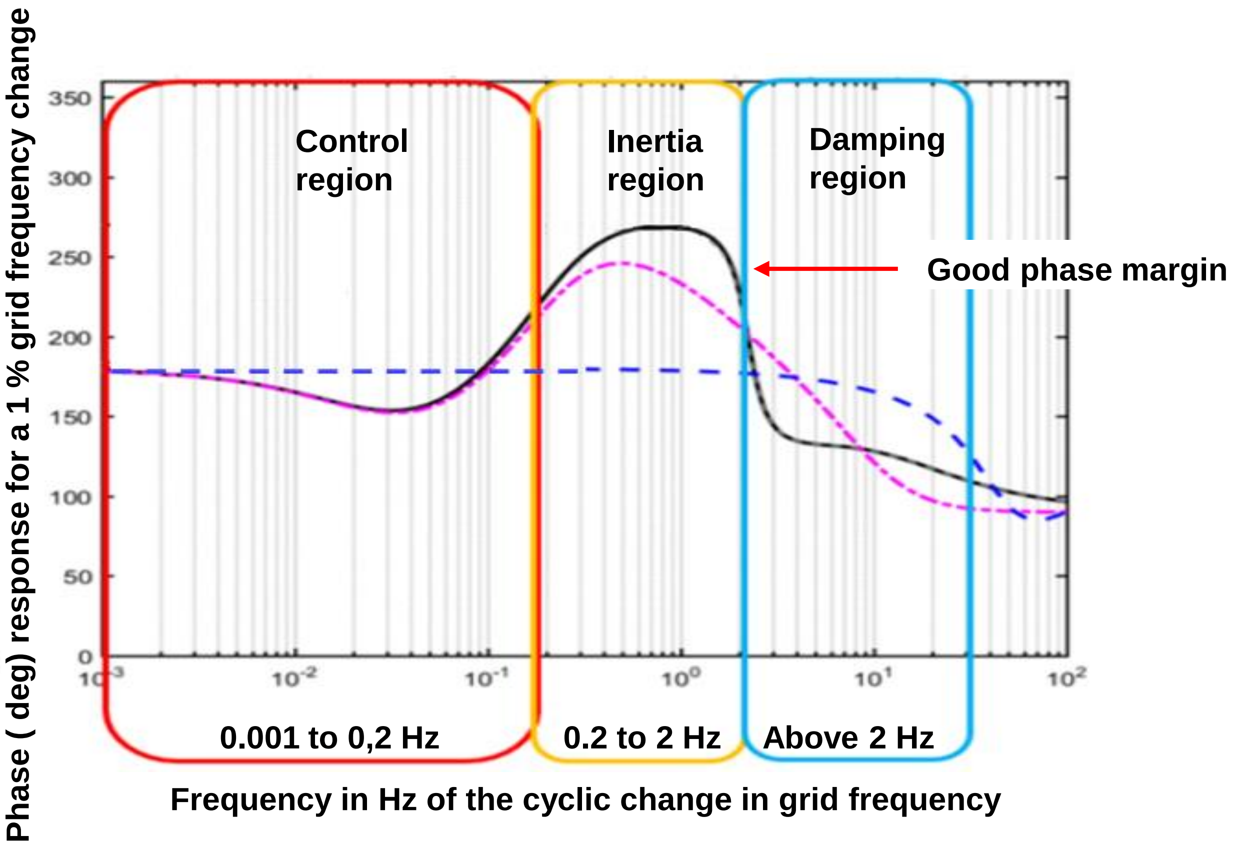
# Effect of changing the Damping Factor



- The systems Damping Factor can be calculated from the values of the Pt damping power and can also be measured on site by the test shown on Slide 40.
- This Chart 1 is then used to find the Damping Factor from the overshoot of either the system’s measured grid power or the measured IVS signal.

# Example of an Network Frequency Perturbation (NFP) Plot ( Bode type plot ) showing the key regions of Response





**Synchronous generator H = 5 and Damping Factor = 0.18.**

**GBGFC H = 5 and Damping Factor = 1.0.**

**VSM0H**

**Extracted from ENTSO-e Figure 1.**
**High Penetration of Power Electronic Interfaced Power Sources**

The input is grid frequency oscillations and output is normally grid power oscillations but can also be used to provide data for either the Fg or Fi frequency signals

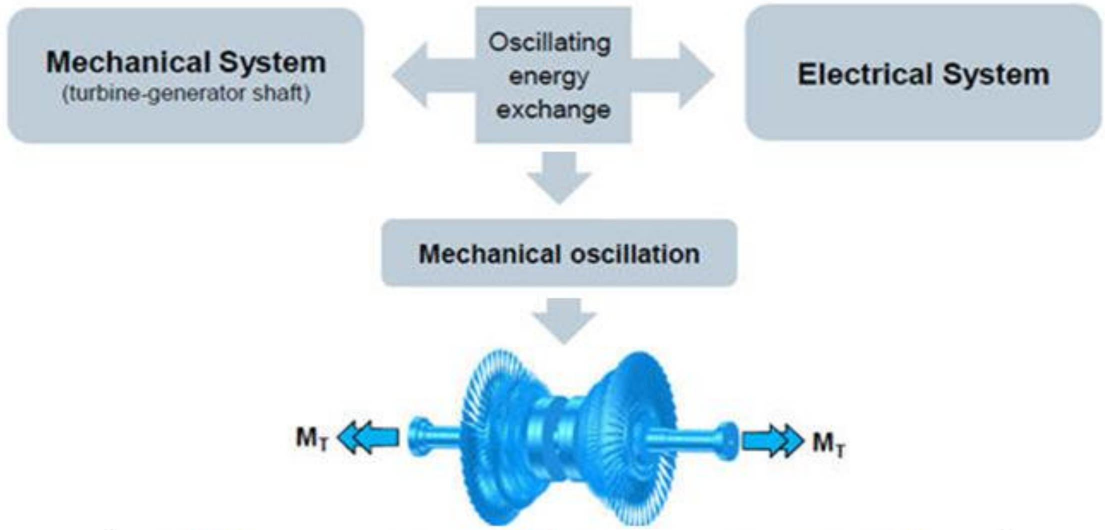
# High Level Grid Code requirements

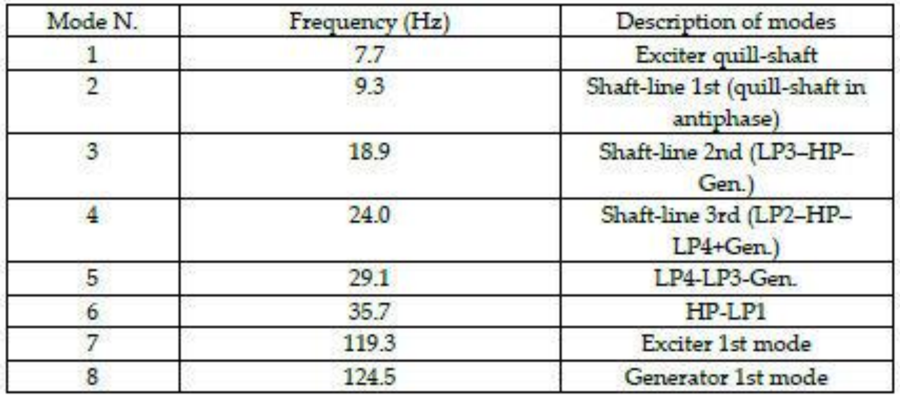
- The Grid Code will need to be updated to reflect the following:-
  - Specification - The ability of the plant to have a Grid Forming Capability
    - ie the ability to operate as a synchronous internal voltage source behind a reactance and the ability to supply inertia power, phase jump power, damping power and controlled power output.
    - Note – The plant is required to have the necessary capabilities and performance but the volume of inertia power, phase jump power, damping power and controlled output power is determined by the developer based on its plant capability.
    - VSM0H whilst not providing any significant inertia is valuable for fault infeed and provision of synchronizing torque but does not provide a full GB Grid Forming response.
    - Parameters submitted by the Developer
  - General model data
  - Compliance (ie the ability to demonstrate the plant can meet the specified technical requirements of the Grid Code)
    - Simulations
    - Testing
- Note GB Grid Forming will not be a mandatory requirement

# Grid Code requirements - Overview

- Builds on the work completed in the Expert Group, through the Stability Pathfinder work and the last workgroup held on 9th April 2020
- Comprises a synchronous internal voltage Source behind an impedance
- Capable of contributing to Inertia Power, Phase Jump Power, Damping Power
- Capable of control of Active and Reactive Power
- All control loops using external inputs have a 5 Hz bandwidth limit
- Satisfy the necessary control system requirements – similar to that of a Synchronous Machine
- Meets the requirements of the European Connection Conditions including Quality of Supply Requirements
- Submit an equivalent model of their plant in addition to the representation in Block Diagram format and parameters of the capability of their plant.
- Present performance of the plant through a Network Perturbation Plot
- Compliance
  - Simulations
  - Tests

# Bandwidth Limiting





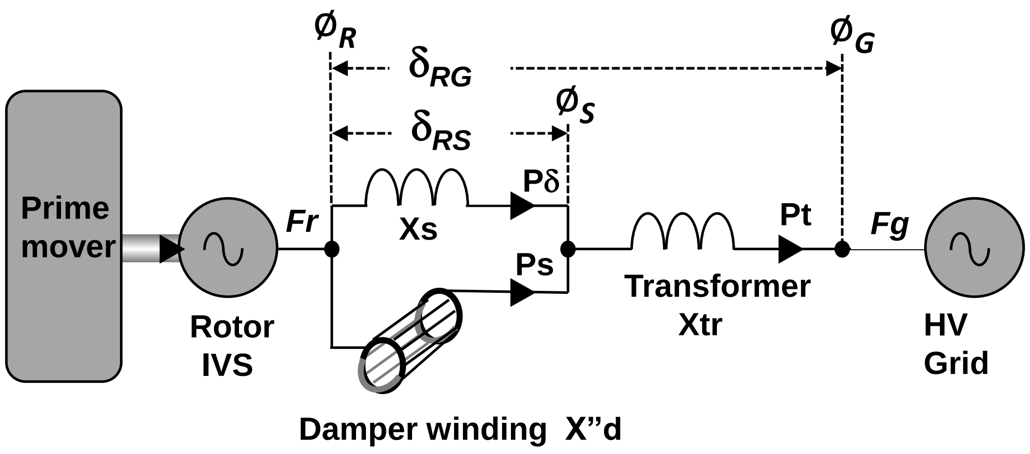
| Mode N. | Frequency (Hz) | Description of modes |
|---|---|---|
| 1 | 7.7 | Exciter quill-shaft |
| 2 | 9.3 | Shaft-line 1st (quill-shaft in antiphase) |
| 3 | 18.9 | Shaft-line 2nd (LP3–HP–Gen.) |
| 4 | 24.0 | Shaft-line 3rd (LP2–HP–LP4+Gen.) |
| 5 | 29.1 | LP4-LP3-Gen. |
| 6 | 35.7 | HP-LP1 |
| 7 | 119.3 | Exciter 1st mode |
| 8 | 124.5 | Generator 1st mode |

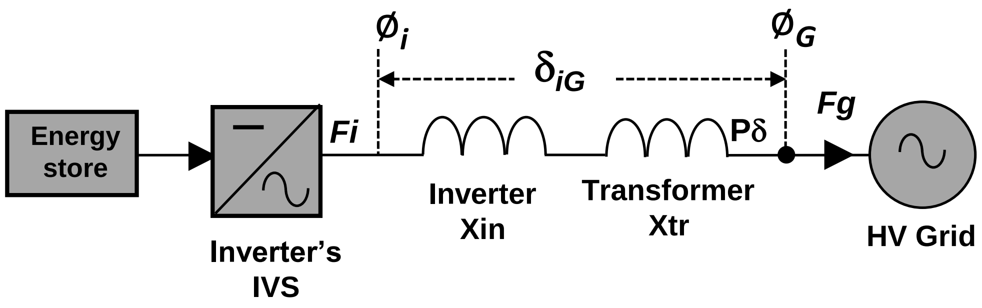
- Suggestion to have “a frequency band of below 5Hz”

  only for changes made via the control system based on external inputs
- This is the reason for the lower frequency limit.
- Can have low frequency grid harmonics within the G5/4 and P28 limits.
- Real Damping power has a bandwidth of 1000 Hz or faster
- Internal control signals can have a bandwidth of 1000 Hz or faster
- Required to avoid undue interactions with other plant connected to the network
- Already specified in the voltage control requirements for Synchronous Generation and Power Park Modules CC/ECC.A.6 and CC/ECC.A.7

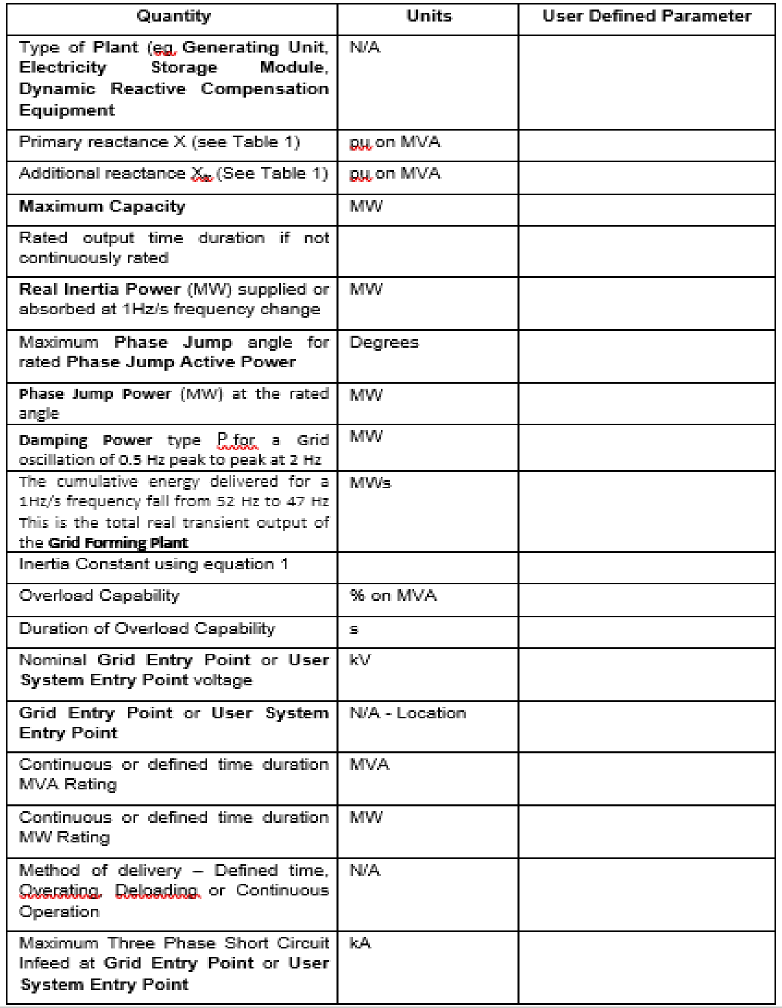
# Data Submission and Model

| Parameter | Symbol | | Unit |
|---|---|---|---|
| | SM | GBGFC | |
| Primary Plant Reactance | X"d | Xin | pu on MVA |
| External Reactance – Plant Terminals to Connection Point | Xtr | Xtr | pu on MVA |
| Angle between internal voltage source and Stator terminals | $\delta_{RS}$ | | radians |
| Angle between the internal voltage source and Connection Point | $\delta_{Rg}$ | $\delta_{ig}$ | radians |
| Voltage and Phase of the Internal Voltage Source of the Grid Forming Unit | $1\angle\phi_R$ | $1\angle\phi_i$ | Voltage 1pu<br>Phase - radians |
| Voltage and Phase of the System at the Connection Point | $1\angle\phi_G$ | $1\angle\phi_G$ | Voltage 1pu<br>Phase - radians |
| The electrical angle between current and voltage at the stator terminals | Power Factor | | Voltage 1pu<br>Phase - radians |
| Damping Factor | ζ | | |

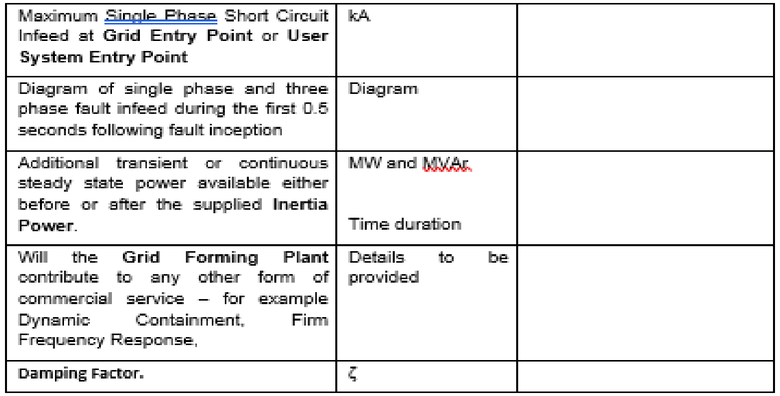




# Capability Data Submission



| Quantity | Units | User Defined Parameter |
|---|---|---|
| Type of **Plant** (eg **Generating Unit, Electricity Storage Module, Dynamic Reactive Compensation Equipment** | N/A | |
| Primary reactance X (see Table 1) | pu on MVA | |
| Additional reactance $X_a$ (See Table 1) | pu on MVA | |
| **Maximum Capacity** | MW | |
| Rated output time duration if not continuously rated | | |
| **Real Inertia Power** (MW) supplied or absorbed at 1Hz/s frequency change | MW | |
| Maximum **Phase Jump** angle for rated **Phase Jump Active Power** | Degrees | |
| **Phase Jump Power** (MW) at the rated angle | MW | |
| **Damping Power** type P for a Grid oscillation of 0.5 Hz peak to peak at 2 Hz | MW | |
| The cumulative energy delivered for a 1Hz/s frequency fall from 52 Hz to 47 Hz This is the total real transient output of the **Grid Forming Plant** | MWs | |
| Inertia Constant using equation 1 | | |
| Overload Capability | % on MVA | |
| Duration of Overload Capability | s | |
| Nominal **Grid Entry Point** or **User System Entry Point** voltage | kV | |
| **Grid Entry Point** or **User System Entry Point** | N/A - Location | |
| Continuous or defined time duration MVA Rating | MVA | |
| Continuous or defined time duration MW Rating | MW | |
| Method of delivery – Defined time, Overating, Deloading or Continuous Operation | N/A | |
| Maximum Three Phase Short Circuit Infeed at **Grid Entry Point** or **User System Entry Point** | kA | |



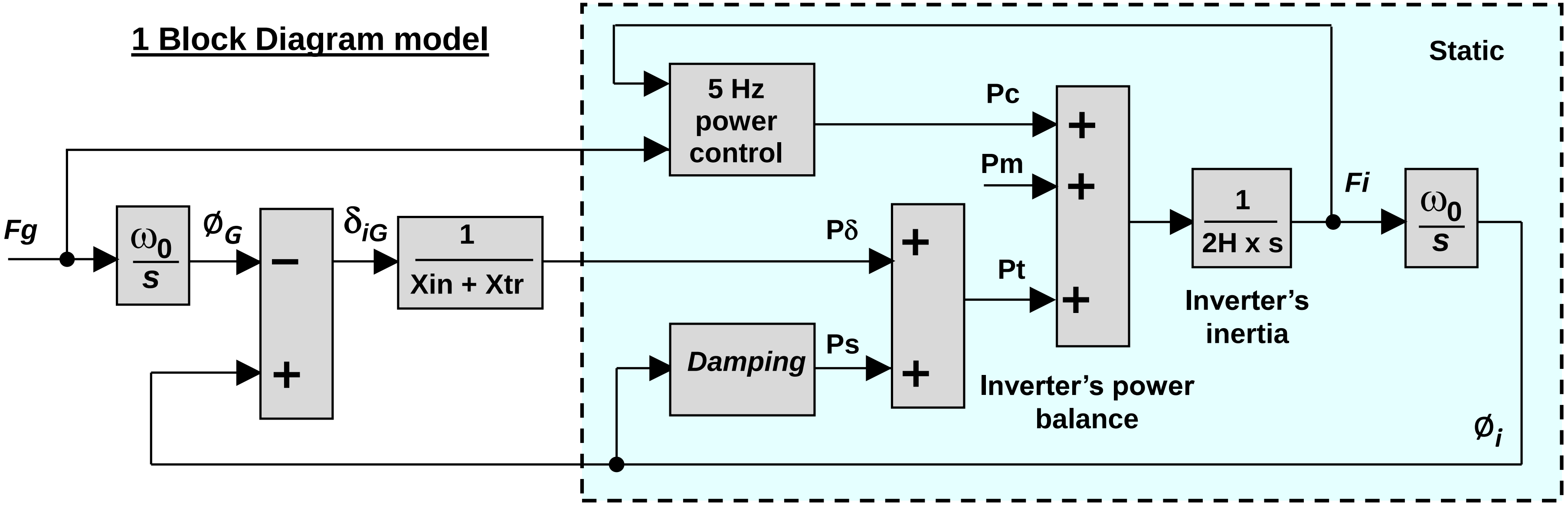
| | | |
|---|---|---|
| Maximum Single Phase Short Circuit Infeed at **Grid Entry Point** or **User System Entry Point** | kA | |
| Diagram of single phase and three phase fault infeed during the first 0.5 seconds following fault inception | Diagram | |
| Additional transient or continuous steady state power available either before or after the supplied **Inertia Power**. | MW and MVAr<br>Time duration | |
| Will the **Grid Forming Plant** contribute to any other form of commercial service – for example Dynamic Containment, Firm Frequency Response, | Details to be provided | |
| **Damping Factor.** | ζ | |

**H = ( Real Inertia Power at 1 Hz / s x Frequency ) / ( Installed MVA x 2 )**

**Equation 1**

# Model Submission, Closed Loop Transfer Function and Network Frequency Perturbation Plot

**1 Block Diagram model**



Taken from Slide 21

**2 Closed Loop Transfer Function**

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s) \times H(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

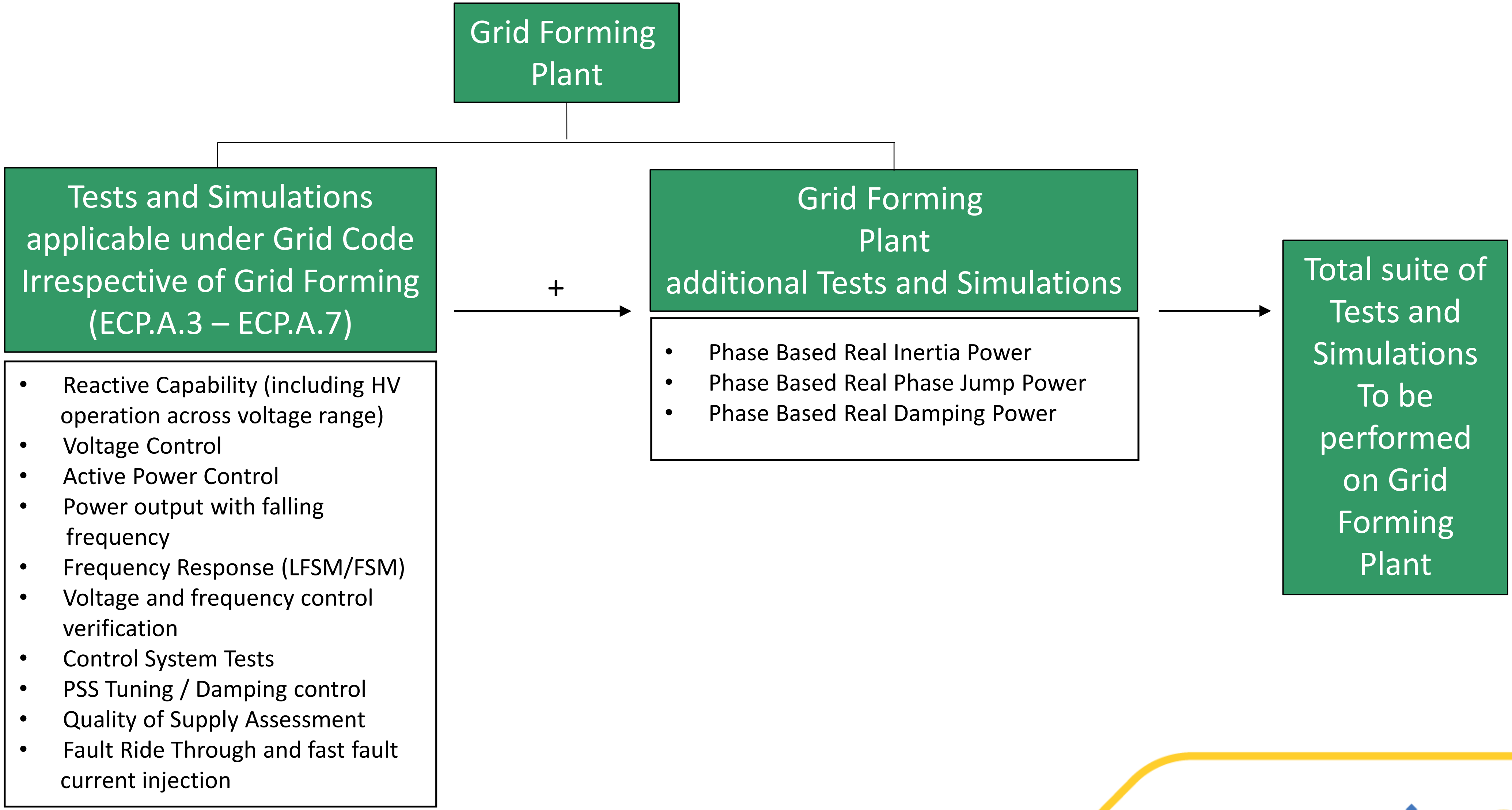
Taken from Slide 22

**3 Network Frequency Perturbation Plot – see slide 25**

# Compliance - Overview

- Demonstrate the plant as built, meets the requirements of the Grid Code and Bilateral Agreement and commercial contract – this would confirm that Grid Forming Capability has been demonstrated.
- Comprises models, simulations and tests
- For a developer who is a CUSC Party, the plant owner would also be required to demonstrate their ability to satisfy their ability to meet all applicable requirements of the Grid Code and Bilateral Agreement
- For Grid Forming simulations and tests would be required to demonstrate
  - The configuration comprises an internal voltage source behind an impedance which generates a synchronous voltage source which is in phase with the System
  - Simulation and Tests to demonstrate Phase Based Inertia Power, Phase Jump Power, Damping Power, controlled Active Output Power and fast fault current injection at rated values up to grid operating limits at a lower power to the specified withstand limits (1 Hz/s Synchronous Generator and 2 Hz/s static power converters)
  - Confirmation that the Grid Forming Plant does not cause undue interactions with the System or other User's Plant and Apparatus through tests, simulations and submission of and Network Frequency Perturbation (NFP) plot
  - Confirmation and demonstration that the Grid Forming Plant can meet the requirements of the Grid Forming Specification detailed in ECC.6.3.19, in particular confirmation that the plant can supply the performance that has been declared in Table 2.

# Compliance – Testing and Simulation - Overview



Grid Forming Plant

Tests and Simulations applicable under Grid Code Irrespective of Grid Forming (ECP.A.3 – ECP.A.7)

- Reactive Capability (including HV operation across voltage range)
- Voltage Control
- Active Power Control
- Power output with falling frequency
- Frequency Response (LFSM/FSM)
- Voltage and frequency control verification
- Control System Tests
- PSS Tuning / Damping control
- Quality of Supply Assessment
- Fault Ride Through and fast fault current injection

+

Grid Forming Plant additional Tests and Simulations

- Phase Based Real Inertia Power
- Phase Based Real Phase Jump Power
- Phase Based Real Damping Power

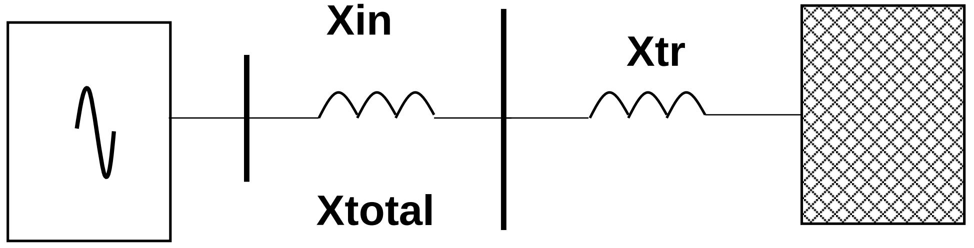
Total suite of Tests and Simulations To be performed on Grid Forming Plant

# Compliance – Signal Testing and Simulations

- For testing and simulation it is vital that fast timesteps and high resolution recording samples are used as many of the characteristics occur almost instantaneously with many of the most important characteristics taking place in the first cycle
- Testing shall be in accordance with ECC.6.6.3. This will require further amendment for Grid Forming Converters. For voltage control tests a sampling rate of 100Hz is currently used (10ms).
- For Grid Forming Converters events will be taking place in one cycle (20ms) and hence a minimum sampling rate of 1000Hz (1ms) will be required. Power Generating Modules of Type C and D are required to be fitted with Dynamic System Monitors which can record up to 256 samples in once cycle (12.8kHz)
- For simulations, variable step length techniques are recommended so for changes in plant output, high resolutions are achieved, whereas in the case of steady state operation, low resolutions are acceptable. A minimum step length of 1ms is deemed to be sufficient to ensure adequate detail yet prevent the risk of non-convergence.

# Demonstration of Phase based Inertia Power (Rated linear)

1) Grid Forming Plant operating in steady state at 50Hz
2) Frequency increased to 50.5Hz at a rate of 1Hz/s from 50Hz.
4) Record Traces of Active Power and Frequency for 10 seconds
6) Determine Grid Forming Active Power injection for a 1Hz/s frequency change for one second to determine Phase Based Inertia Power injected
7) The test is conducted to ensure basic operation in the linear region without going in to power limitation



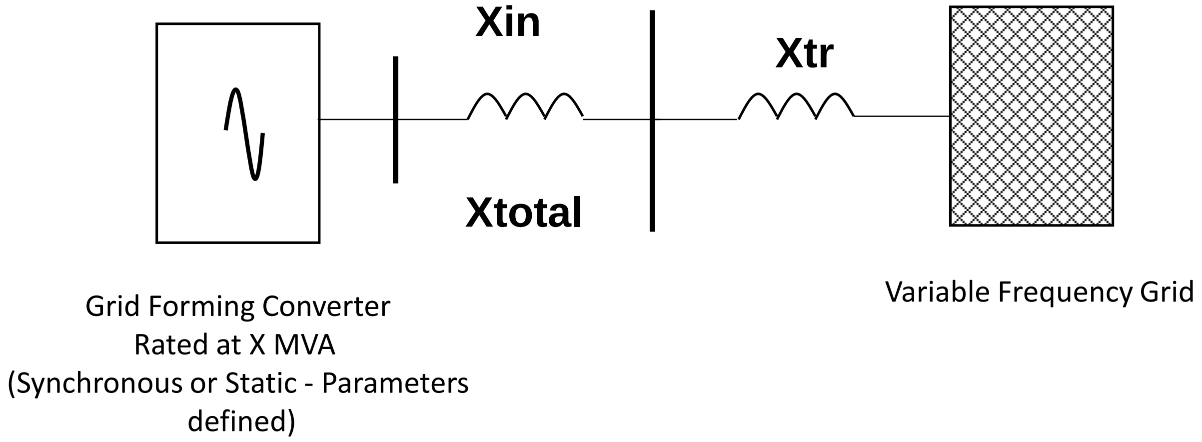
Grid Forming Converter
Rated at X MVA
(Synchronous or Static - Parameters defined)

Variable Frequency Grid

Note Xin applies in the case of static power converters and Xd'' applies in the case of Synchronous Generators

# Demonstration of Phase based Inertia Power (Withstand)

1) Grid Forming Plant operating in steady state at 50Hz
2) Determine Grid Forming Active Power injection for a ±1.0 Hz/s frequency change (rotary) and ±2 Hz /s (static) for one second to determine Phase Based Inertia Power injected
3) The test is conducted to ensure basic operation in the withstand region with going in to power limitation for static

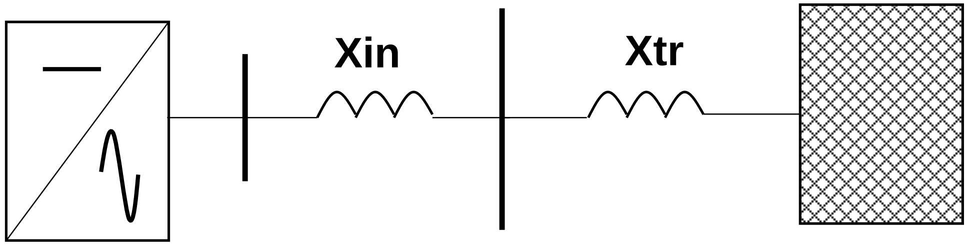


Grid Forming Converter
Rated at X MVA
(Synchronous or Static - Parameters defined)

Variable Frequency Grid

Note Xin applies in the case of static power converters and Xd’’ applies in the case of Synchronous Generators

# Demonstration of Phase based Inertia Power over the full Frequency Range



Grid Forming Converter
Rated at X MVA (Parameters
defined by Developer)

Variable Frequency Grid

1 Grid Forming Plant operating at 75% full load, zero MVAr and in steady state.

2) Frequency – 50Hz and Grid Forming Plant operating with no added control

3) Frequency of Grid increased from 50Hz – 52Hz at 1Hz/s from 5 to 7 seconds

6) At 12 to 17 seconds Frequency of Grid reduced from 52Hz to 47Hz at 1Hz/s and record until 20 seconds

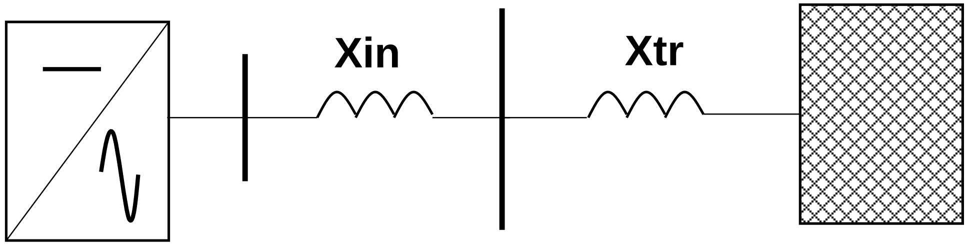
7) Record Traces of Active Power, Reactive Power, Voltage and Frequency for a further 10 seconds

8) Must deliver real Power current stably over this test without going into power limitation and pole slipping should not occur

9) Repeat above steps from 50Hz – 47Hz and then up to 52Hz

10) Confirm Grid Forming Plant delivers Phase based inertia power as declared

# Demonstration of Phase Jump Active Power



Grid Forming Converter Rated at X MVA (Parameters defined by Developer)

Variable Frequency Grid

1 Grid Forming Plant operating at full load, zero MVAr and in steady state.

2) Frequency – 50Hz and Grid Forming Plant operating with no added control

3) Apply a phase jump of 10 degrees at the Grid Entry Point at 10 seconds

4) Record Traces of Active Power, Reactive Power, Voltage , Current and Frequency at 5 seconds and record for a further 10 seconds

5) Confirm correct operation of Grid Forming Plant

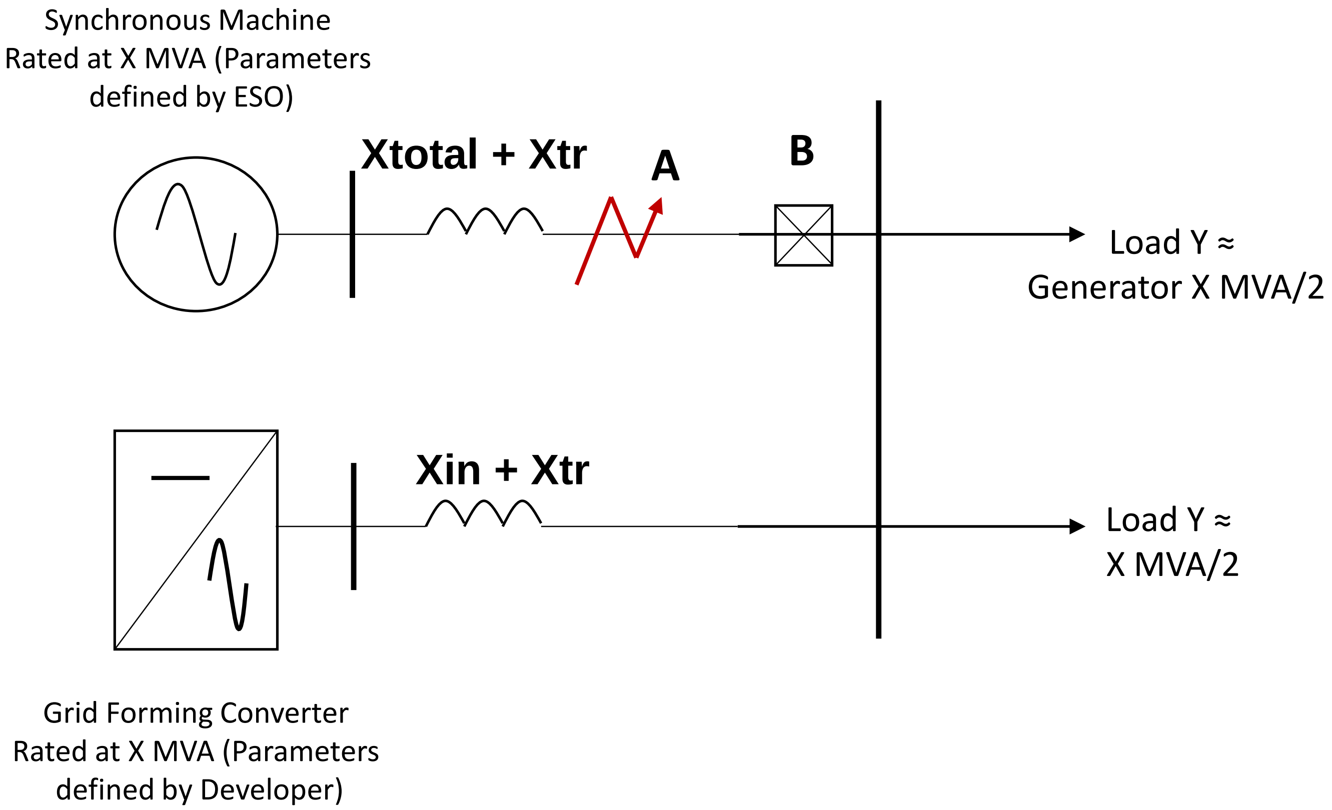
6) Repeat steps 1 – 5 with a Phase jump of 50 degrees when operating at minimum output and confirm correct operation

7) Repeat steps 1 – 5 and apply a solid three phase short circuit fault at the Grid Entry Point for 140ms.

8) Remove the fault and observe the results

# Demonstration of Phase based Inertia Power and Phase Jump Power under Extreme Conditions

1) Synchronous Machine and Grid Forming Plant operating at load Y, zero MVAr and in steady state
2) Frequency – 50Hz and both generators operating with no added control
3) Solid three phase fault applied at point A at 5 seconds
4 Circuit Breaker B opened 140ms from inception of Fault A (ie 5.14 seconds)
5) Record Traces of Active Power, Reactive Power, Voltage and Frequency and record for a period of 5 seconds after fault inception



# Testing the damping power of grid forming static power converters

**Simulation model**

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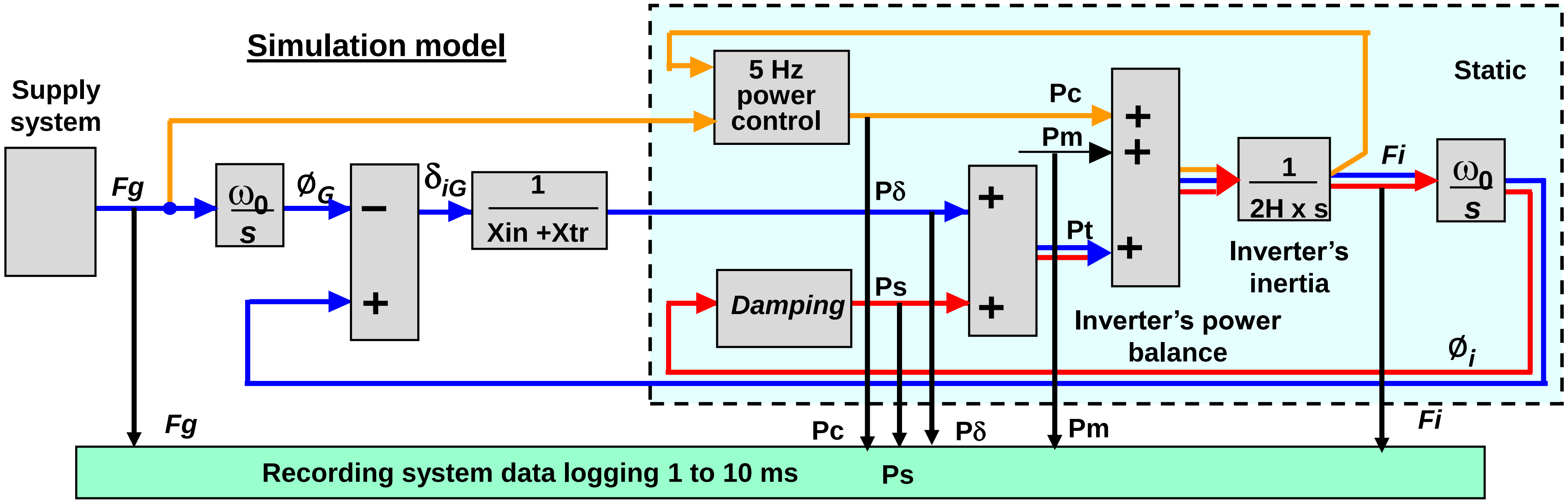

There are three types of damping power with GBGF static power converters:

- The Type 3 real Phased based Damping power - shown by the **Blue** lines which is real Phase based Damping power flowing via the invertor's impedance.
- The Type 4 real Control based output power – shown by the **Orange** lines which is provided by the power control that has a < 5 Hz frequency response limit.
- The Type 3 software damping of the software inertia – shown by the **Red** lines which is provided by the "*Damping* " function is defined by the parameters of the Inverter's control system and is the supplier's IPR.
- This has no real power flow and can use higher damping values compared with synchronous machines,
- Apply a 2 Hz sinewave with a peak to peak amplitude of 0.5 Hz and measure damping AC power. Test for Pd only, then Pd + Ps, then Pd + Pc and Pd + Ps + Pc
- A good way to measure the Damping Factor ( Zeta ) is by either the overshoot ratio or by the decay per cycle ratio.

# Site Testing Facilities

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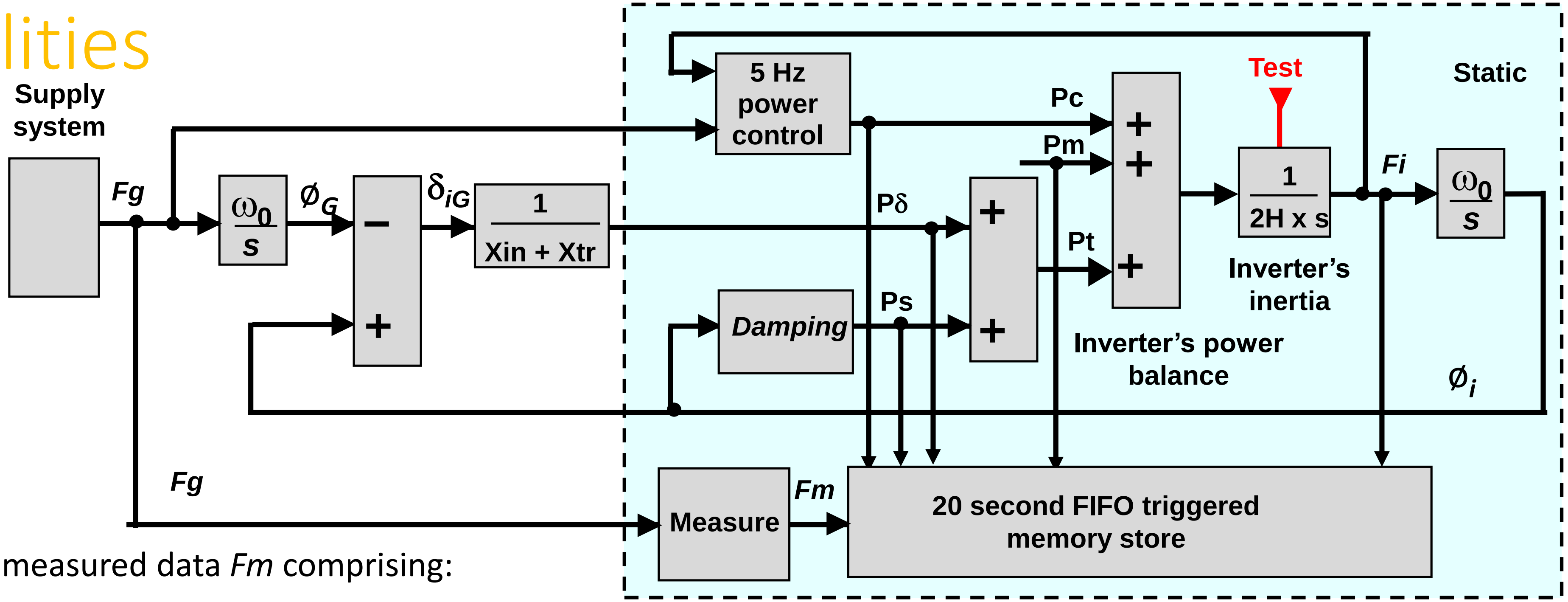


These are typical features:

- Measuring system for *Fg* to give measured data *Fm* comprising:
    - Calculated Frequency at a 10 ms rate, with high immunity to phase jumps.
    - Calculated RoCoF at a 10 ms rate, with high immunity to phase jumps.
    - Calculated Phase Jump data.
- A twenty second First in First out "FIFO" data store with a new input every 10 ms and stopped after 10 s by input triggers outside of a pre-set value for Frequency, RoCoF and Phase jumps.
- Storage of each set of the captured data for 10 s before and 10 s after an event that is then stored for retrieval.
- A FIFO store that is restarted to catch subsequent events and the stored data is retrieved via the internet with an accurate GPS time stamp.
- Test damping for Pd only, then Pd + Ps, then Pd + Pc and Pd + Ps + Pc and a good way to measure the Damping Factor ( Zeta ) is by either the overshoot ratio or by the decay per cycle ratio.
- A test input to give a pre-set phase jump in *Fi* for a lab and site test ability for measuring damping.

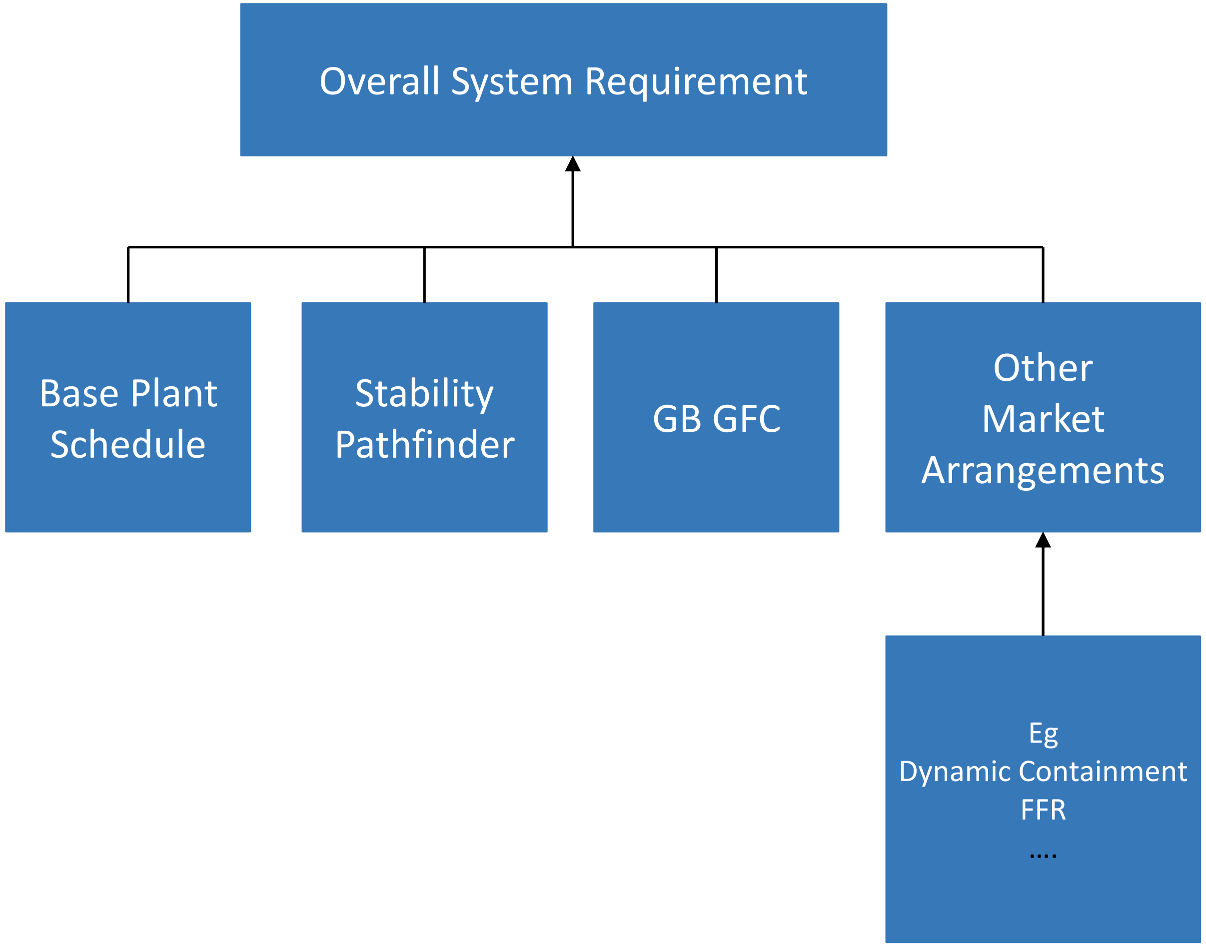
# Monitoring

- In addition to simulation and testing once a Grid Forming Plant has been issued with a Final Operational Notification online monitoring is undertaken to ensure the plant continues to satisfy the requirements of the Grid Code and Bilateral Agreement
- Dynamic System Monitoring (DSM) is currently used for this purpose – the requirements are detailed in the Annex to the General Conditions as one of the Relevant Electrical Standards – TS.3.24.70
  - https://www.nationalgrideso.com/document/33196/download
  - DSM currently has the capability to record 256 samples per cycle – (12.8 kHz)
  - The option could be considered to assess the DSM and output from recorded / witnessed tests
- DSM is a mandatory requirement for all Type C, Type D Power Generating Modules, HVDC Systems and DC Connected Power Park Modules

# Determination of System Need

- It is for the ESO to determine the volume of Grid Forming required (ie Phased Based Real Inertia Power, Phase Based Phase Jump Power and Damping Power). This will be based on a regional and national basis.
- The requirement will be made up of:-
  - Plant running in the basic plant schedule
  - Plant procured through the Stability Pathfinder work
  - Plant procured through the GB Grid Forming Market
  - Additional services contributing in the longer term timescale – eg Dynamic Containment, Frequency Response, STOR, Reserve etc (ie stackable services)
- Note – Grid Forming plant has the capability to contribute to Short Circuit Level and hence fast fault current injection both with and without inertia.
  - Hence there are opportunities for Grid forming static Power Converter (inertia) and none Grid forming VSM0H (no inertia)
- Note in a system made up of Synchronous Generation where inertia, synchronising power damping power etc were free, these products will **now have to be paid for.**
- The ESO needs to operate a safe, secure and economic System at minimum cost

# Interaction with other Initiatives / Markets



# Key Points

- Conventional Power Electronic Converters do not contribute Phased Based Inertia Power, Phase Based Phase Jump Power or Phase Based Damping Power.
- A Grid Forming Converter needs to contribute to these requirements
- Traditionally these requirements were provided for free – inherently through the reliance on synchronous generation. In the future these requirements will have to be paid for
- Grid Forming is a key enabler to achieve this. Other techniques include using more synchronous generation or using synchronous compensators. The more available solutions the cheaper the cost
- Grid Forming with inertia (**GBGFC**) and None Grid Forming without inertia (VSM0H) will all play a part in helping to secure the system during and after fault conditions
- It is not possible to cover all detailed aspects in this presentation but further material is available – see slide 47

# Next Steps

- Discuss current specification and proposals
- Comments on latest specification
- Discuss tests and simulations
- Develop Legal text for Compliance
- Discuss data requirements

# References / Further Information

- Design of GB Grid Forming Converters – E A Lewis – Enstore
- Enstore’s GFC basic testing data – E A Lewis – Enstore
- SGRE Response to VSM Grid Code Spec V6_AJ010420 – Siemens Gamesa Ref GC0137 20200430 SGRE Response to VSG_Grid_Code_Draft_Specification_V6_AJ010420 R1.docx.docx – Andrew Roscoe – Siemens Gamesa
- Questions on GC0137 for Discussion - Alastair Frew – 20 April 2020
- High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS) - ENTSO-E Guidance document for national implementation for network codes on grid connection dated 29 March 2017

# Symbols

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| | |
|---|---|
| $\delta_{iG}$ | **Angle between Inverter and Grid** |
| $\delta_{RG}$ | **Angle between Rotor and Grid** |
| $\delta_{RS}$ | **Angle across Rotor impedances** |
| ***Fg*** | **Frequency of the Grid** |
| ***Fi*** | **Frequency of the Inverter voltages** |
| ***Fr*** | **Frequency of the Rotor voltages** |
| **D** | **Gain of damping parameter** |
| **GBGF(C)** | **GB Grid Forming ( Converter)** |
| **H** | **Inertia in per unit** |
| $P\delta$ | **Power in impedances** |
| **Pc** | **Power of the slow control system** |
| **Pm** | **Mechanical input power** |
| **Ps** | **Power due to slip in Damper windings** |
| **Pt** | **Sum of Pd and $P_S$** |

| | |
|---|---|
| $\phi_G$ | **Phase angle of the Grid voltages** |
| $\phi_i$ | **Phase angle of Inverter voltages** |
| $\phi_R$ | **Phase angle of Rotor voltages** |
| $\phi_S$ | **Phase angle of Stator voltages** |
| ***s*** | **Derivative function** |
| 1 / ***s*** | **Integrating function** |
| $\omega_0$ | **Nominal system frequency** |
| **Xs** | **Reactance of stator windings** |
| **X”d** | **Reactance of damper winding** |
| **Xin** | **Reactance of Inverter filter** |
| **Xtr** | **Reactance of supply transformer** |
| **X total** | **Total impedance of a generator** |