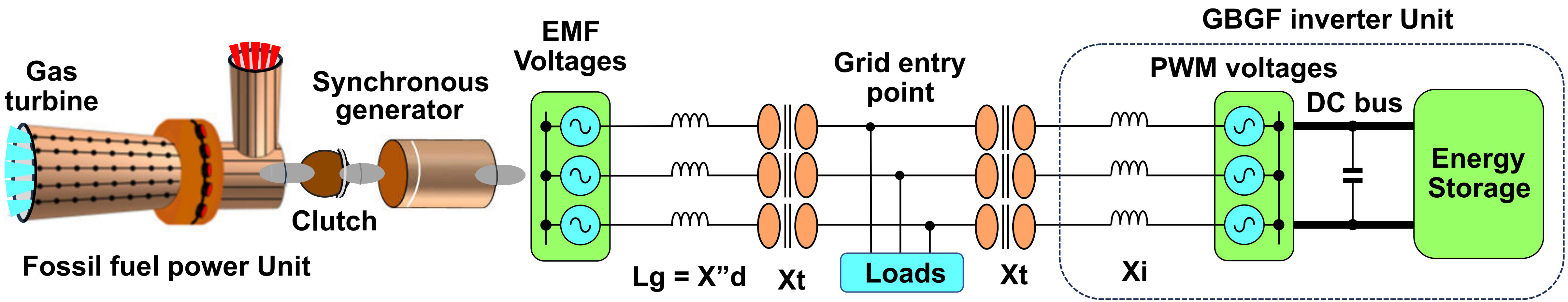
How to combine existing and new Units in an optimised future GB AC Grid

PowerEx Live Midlands on 27 June 2024 at The BELFRY



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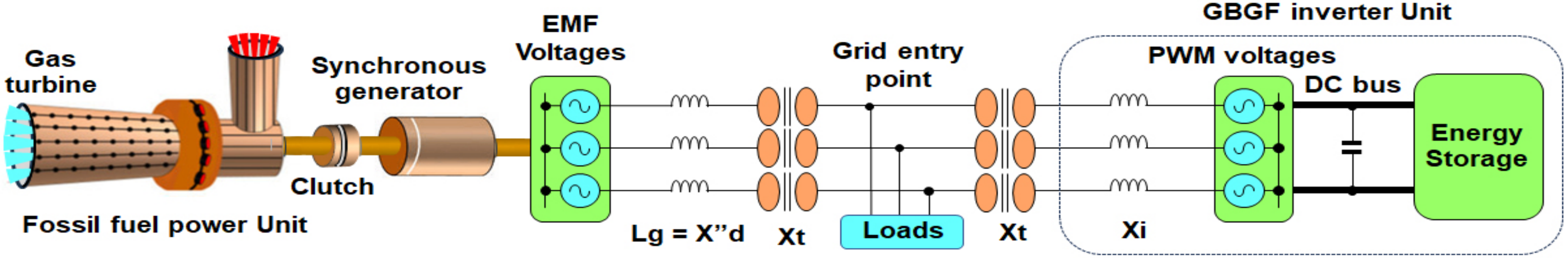
This power point presentation is **Enstore's IPR.**

Part 1. Important background information

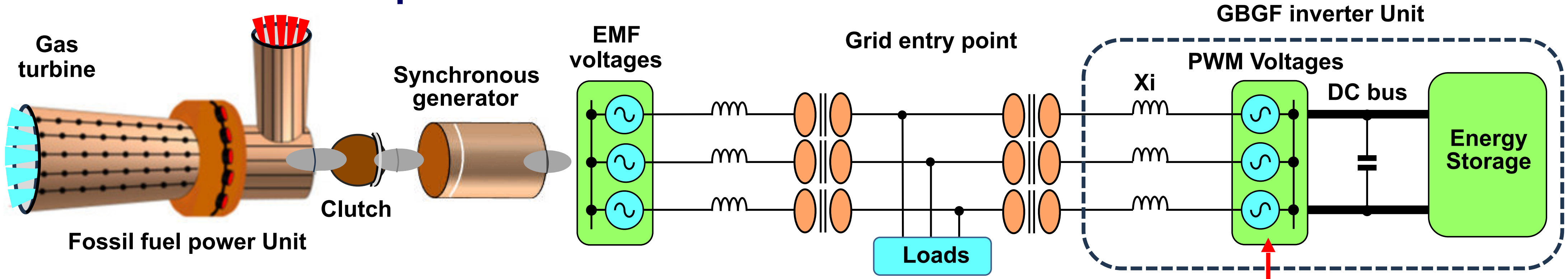


- For a power transient the Synchronous generator instantly allows the flow of power from its inertia via it's **EMF** voltages, that is now called **Active Phase Jump Power.** This limits the change in the Grid's **Phase Jump Angle** and gives a **Stable GB AC Grid.**
- The primary aim of a **Grid Forming** inverter is to provide the identical response when it is operating below its **Current Limit.**
- This is defined in the **EU** data as a **Grid Forming** inverter must not change its output voltage for these conditions, below current limit, to allow the instant flow of **Active Phase Jump Power.** This requires a very slow response by a **Grid Forming** inverter.
- Unfortunately the existing GB Grid Code is not sufficiently clear on this topic and can be read as requiring a very fast control action by a **GB Grid Forming "GBGF"** inverter, which is not allowed. This needs an urgent update to the GB Grid Code.
- The **Short Circuit Level** calculations do not correctly predict the change in the Grid's **Phase Jump Angle** which is why the **Effective Transient Impedance Value "ETIV"** method was developed to correctly predict the Grid's **Phase Jump Angle.**
- This has made it possible to propose the Grid's maximum **Allowed Phase Jump Angle "APJA"** that is needed for calculating the **Current Limit** for **GBGF** inverters and for a proposed **Type Test** for all inverters to validate that they provide **Reliable Grid power.**
- Also a future Grid needs a minimum defined **Damping Factor**, and a proposed value is of 0.7 p for a **Stable GB AC Grid.**

Notes:

- This presentation is based on the data in the **Enstore's New Data Documents** that are available and fully define the operation of **GBGF** inverters and AC Grid systems and how they can provide reliable AC Grid power.
- The words in **bold text** are terms defined and used in the GB Grid Code that needs an urgent update to include new data.
- All the data in this presentation represent **Enstore's** opinions of what could occur in a future GB AC Grid.

The essential black box requirements of a GBGF inverter



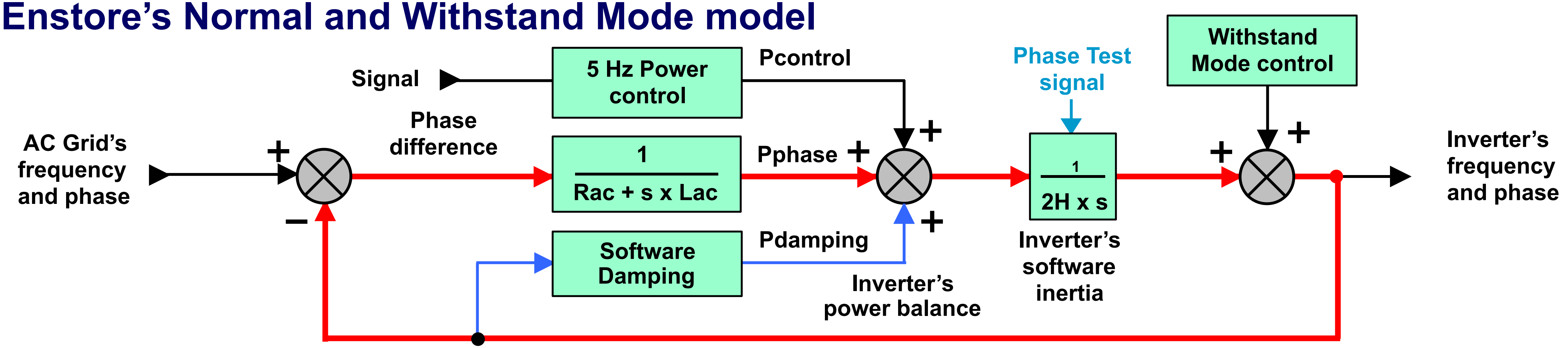
A **GBGF** inverter has several essential black box requirements when operating in its **Normal Mode** below its **Current Limits:**

- It operates like a synchronous generator.
- It has 3 phase positive sequence output voltages that only change slowly.
- It has an AC impedances giving a well defined **Xi** value that is used for calculating the overall **ETIV** Grid stability.
- It has an Energy Storage System "**ESS**" to supply the required power and energy as defined in the **GBGF** Grid Code.
- It has the ability to allow the flow of the instant **Active Phase Jump Power** for a **Phase Jump Angle** to stabilise the Grid, and most importantly, this happens without any control actions by the inverter's control system.
- This is immediately followed by the controlled supply of **Active Inertia Power** to limit the Grid's **RoCoF** rate.
- It has a slow 5 Hz response to the requests for power changes up to its **Current Limits** to give a very stable system.

This corresponds to the proposed **EU** requirements for Grid Forming inverters but the existing GB Grid Code data is " *the transient injection or absorption of **Active Power** from a **Grid Forming Plant** that starts to respond within less than 5 ms*". This can be taken to mean that a **GBGF** inverter needs a fast acting control system to supply the **Active Phase Jump Power** which is not correct**.** The GB Grid Code is going to be updated and existing **GBGF** inverters may not provide these benefits.

A **GBGF** inverter also has a **Withstand Mode** with a faster response to provide a **Fault Ride Through** ability for Grid short circuit faults and to provide its rated output up to the GB AC Grid's maximum **Allowed Phase Jump Angle.**

The Enstore's Normal and Withstand Mode model



The **Normal Mode** controls are generally in operation including:

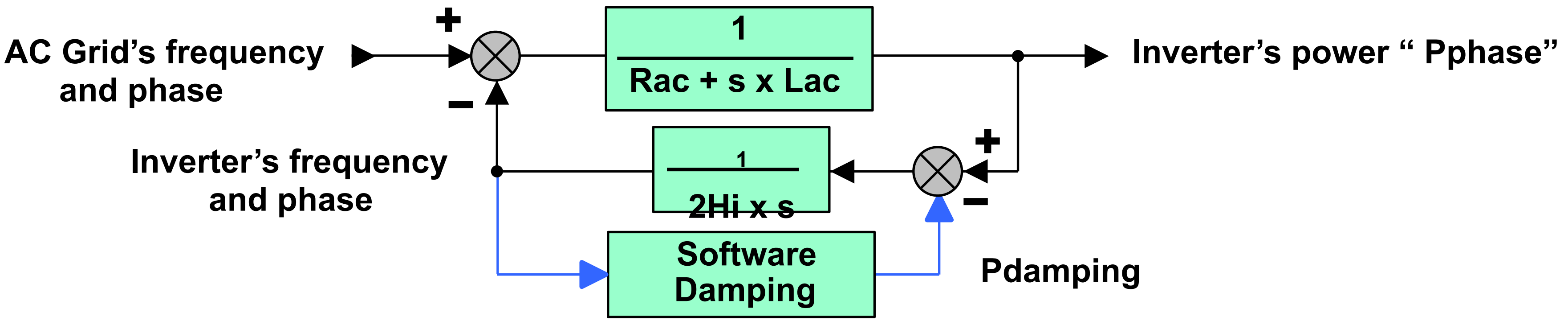
- A closed loop, in **Red**, to maintain the inverter's synchronism to the AC Grid that has a resonant mode frequency, defined by **Lac** and **2H,** with a software **Damping** function to provide an onsite adjustable system **Damping Factor** for this resonant mode.
- The **Rac + S x Lac** function that is essential to give correct **EMT** simulations.
- A **5 Hz Power control** function to allow the system's instant **Active Phase Jump Power** to flow in the AC supply.
- A software **2H x s** function to provide the system's **Active Inertia Power** response.

When the inverter's current is about to go into either of its **Current Limits** the fast acting **Withstand Mode** controls act to keep the inverter at the optimum output without tripping, and the three **Withstand Mode** conditions are:

- ➢ **WM1.** Is for a **Phase Jump** angle changes larger than the **GBGF** inverter's **Phase Jump Angle Limit** rating. The **WM1** mode needs the **Phase Jump Power Current Limit** function based on a fast **PLL** type control.
- ➢ **WM2.** Is for a **RoCoF** rate that is faster than the defined maximum, with a spill over limit maintains synchronisation to the Grid.
- ➢ **WM3.** Is for voltage transients, like Grid faults, which can cause the inverter to reach its **Peak Current Limit** value. The **WM3** mode can use the **Grid Fault Ride Through** control that has been proven for renewable power systems.

- A **GBGF** inverter is only in the **Withstand Mode** for a very short time before returning to the **Normal Mode**.

The use of ENTSO-e Network Frequency Perturbation "NFP" plots to show a system's response

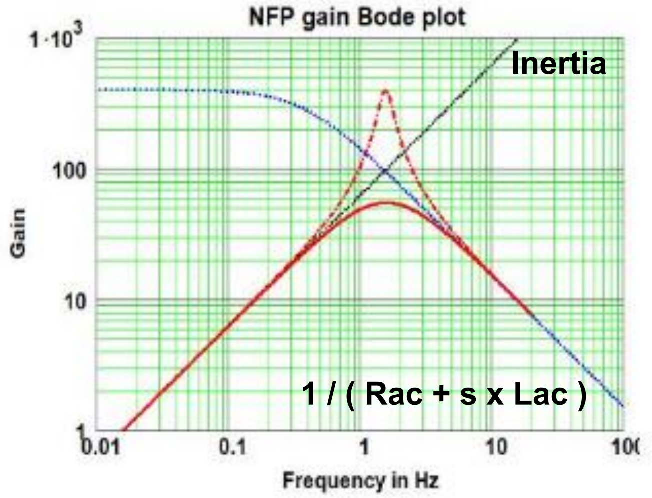


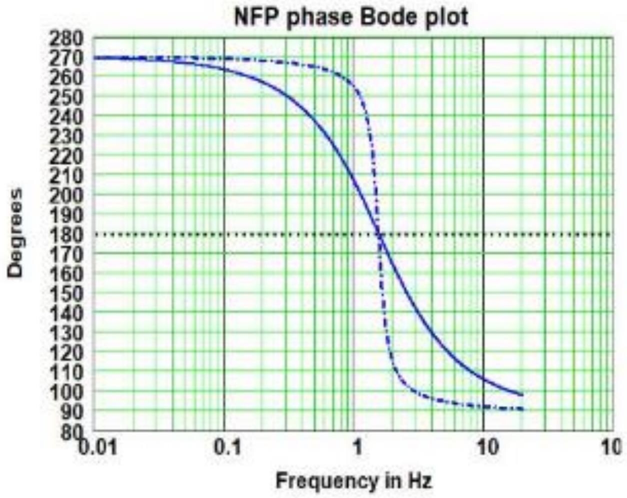
NFP plots show the gain & phase of the inverter's power "**Pphase**" versus the AC Grid's frequency.

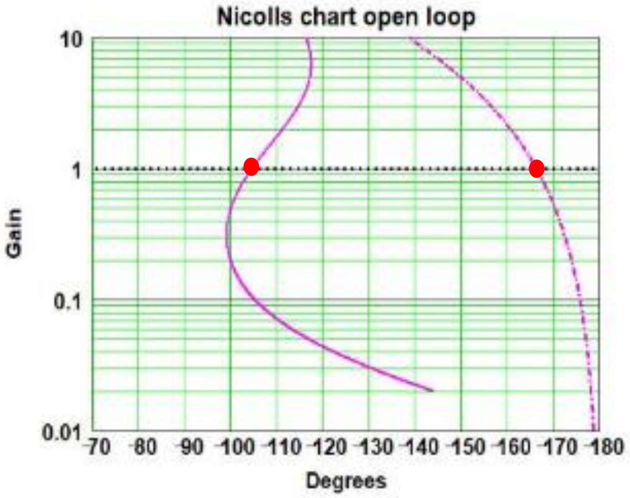
- This data shows a **NFP** gain plot, a **NFP** phase plot and a **Nichols** plot with the same resonant frequency of 1.55 Hz.
- The plot with the dotted lines only has damping from the AC system while the plot with solid lines has damping added by the **Software Damping** function.

These plots are used at the initial stage of a project to have the **NGESO's** approval for:

- The system's low frequency inertia.
- The system's resonant frequency, with limits on the allowed upper and lower resonant frequencies.
- The system's **Damping Factor.**
- An **Enstore** study has data on the allowed values.

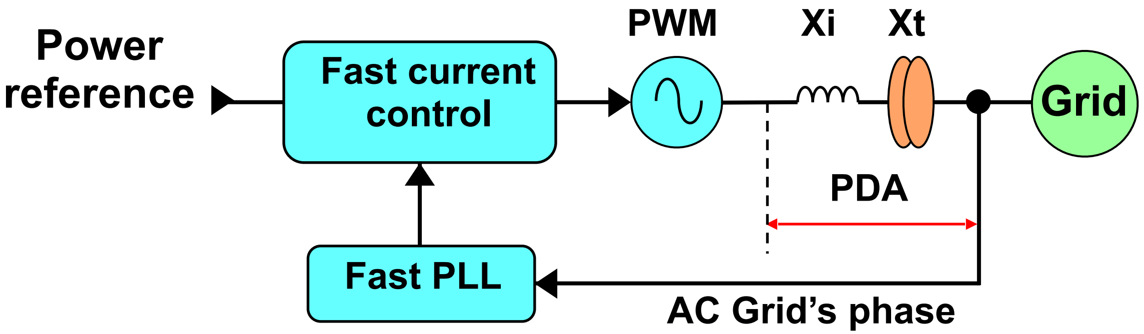




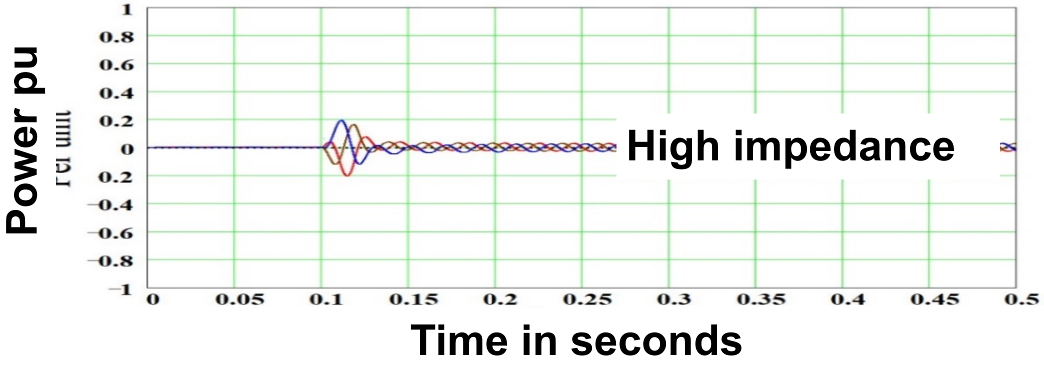


Grid Following “GFOL” and GB Grid Forming “GBGF” inverters

Grid Following inverter

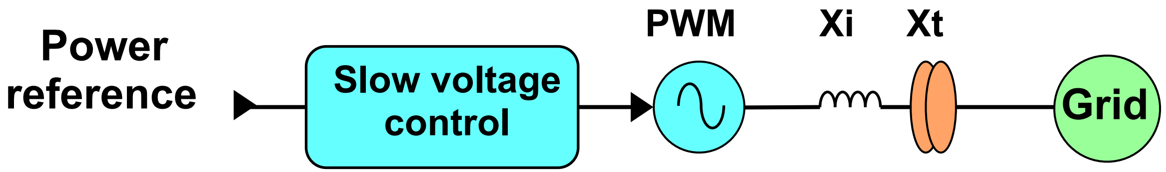


Response to a Phase Jump Angle

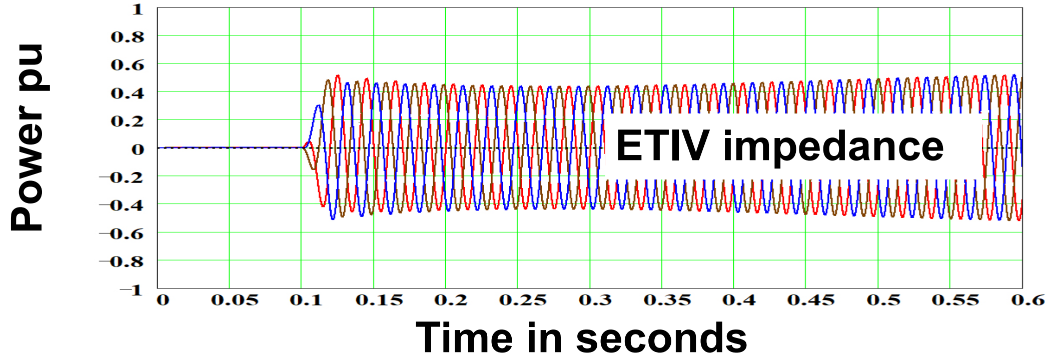


- The existing **GFOL** inverters have a fast signal of the AC Grid’s phase into the Phase Locked Loop “**PLL**” control to very rapidly stop all AC Grid **Phase Jump Angle** changes altering the inverter’s AC Power.
- This stops the inverter supplying **Active Phase Jump Power.**
- The inverter has a fast current control to supply **SCL** current.

Grid Forming inverter



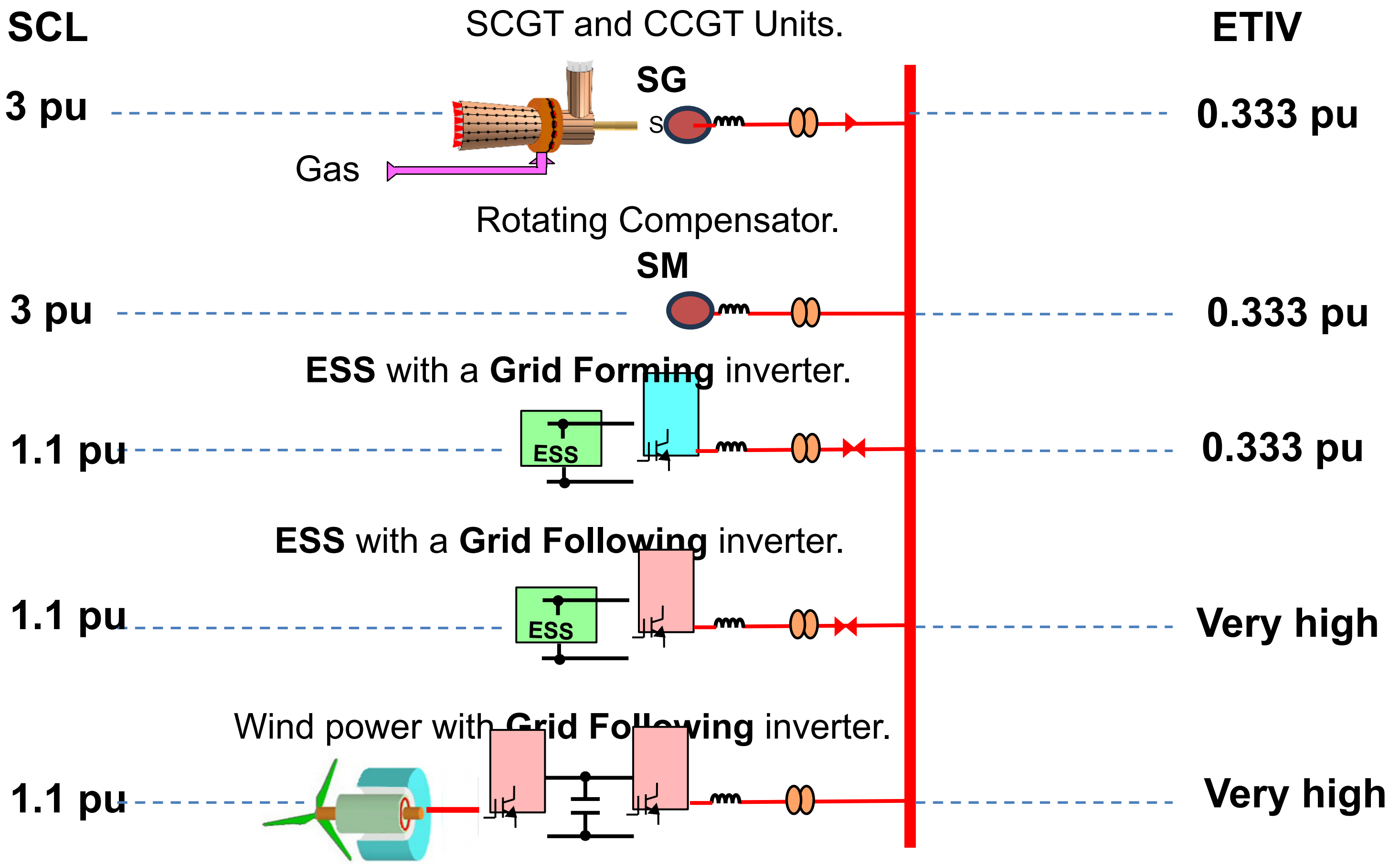
Response to a Phase Jump Angle



- For **GBGF** inverters in the **Normal Mode**, below either **Current Limit**, they have a slow voltage control with a 5 Hz bandwidth.
- This allows the flow of instant **Active Phase Jump Power.**
- If either **Current Limit** is reached the inverter changes to the **Withstand Mode** with a fast acting **Current Limit** response.
- They also supply the defined **SCL** current.
- The GB Grid Code requires an update to fully define the required performance of **GBGF** inverters.

Short Circuit Level “SCL” and Effective Transient Impedance Value “ETIV”.

ESS = Energy storage system.
SG = Synchronous generator.
SM = Synchronous machine.



- A synchronous generator and a synchronous machine have a typical **SCL** current of 3 pu that gives an **ETIV** value of 0.333 pu.
- In this slide all **Units** have the same per unit AC supply impedances.
- For a **GBGF** inverter its **ETIV** value is its AC supply impedance and a **GBGF** inverter also provides the **SCL** current.
- For an existing **Grid Following** inverter with **PLL** control, its **ETIV** value is very high but it does provide the **SCL** current.
- The **ETIV** calculation is **Grid Angle = Asin (Power pu** x **ETIV pu**) with the same pu base for the **Power** and **ETIV**.

Grid frequency and Grid RoCoF rates in the Local and Remote Grid Zones

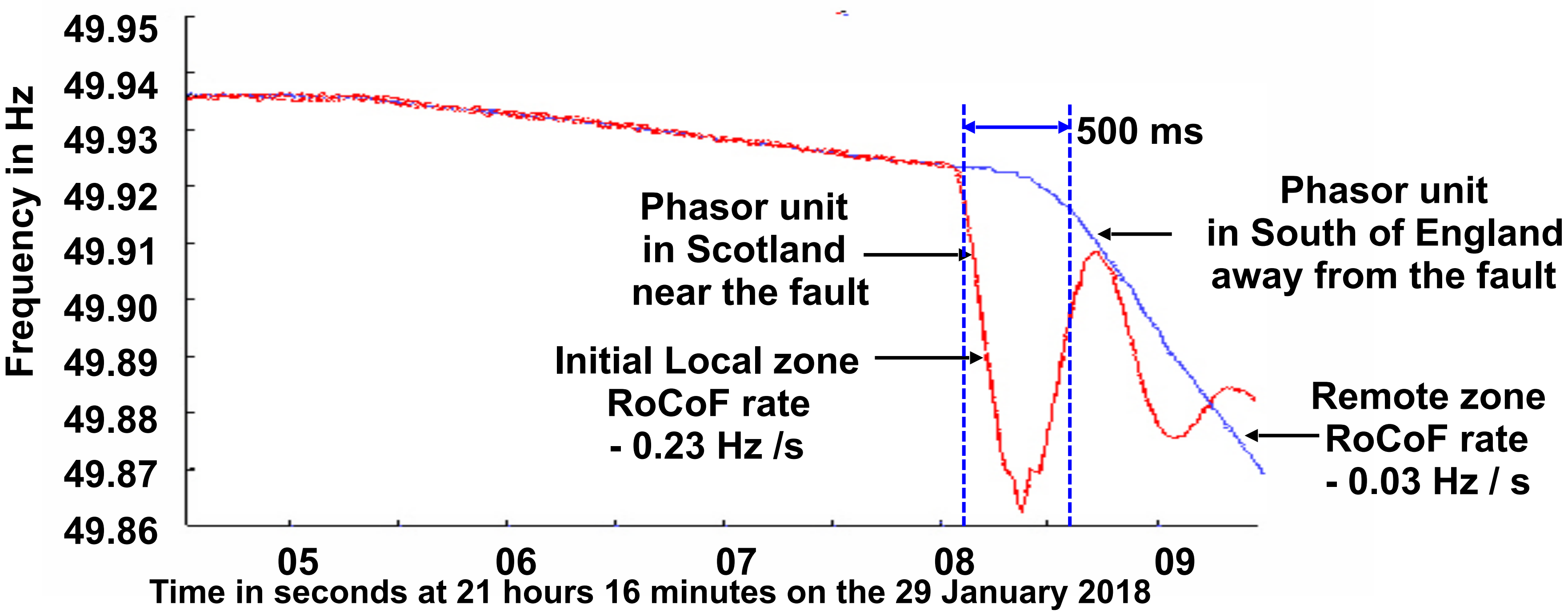
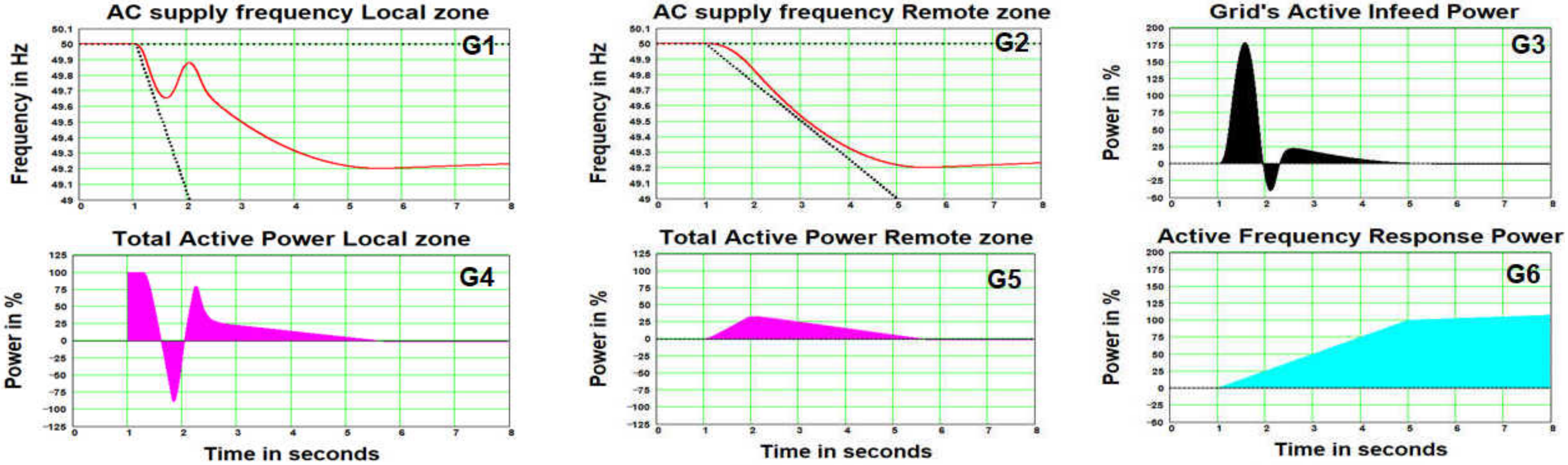


Image based on data in the EFCC and NGESO public domain archives

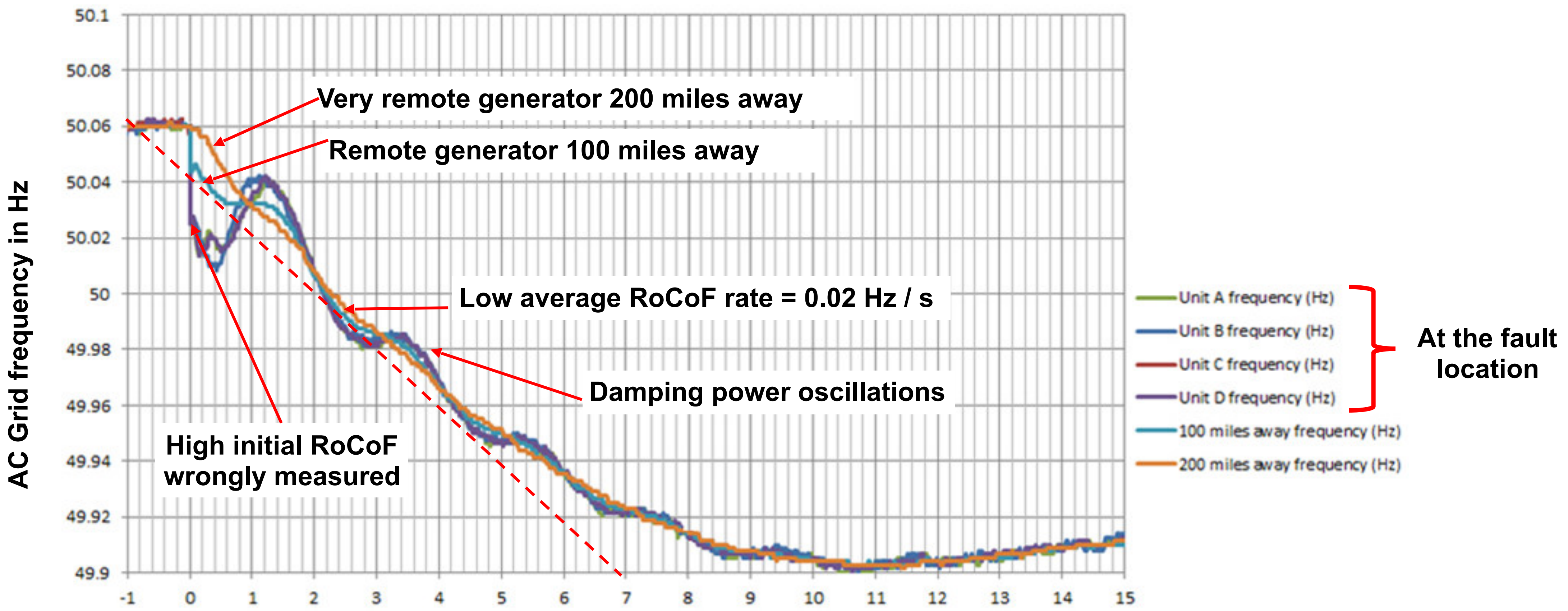
- For a power transient the effects are the highest near to the transient, called the **Local zone**, and lower in the rest of the Grid called the **Remote zones**.
- The **Local zone** frequency:
  - ➢ Has a higher **RoCoF** rate compared with the rest of the **Remote zones.**
  - ➢ Becomes aligned with the **Remote zones** in about one second, this is important for rating Energy Storage Systems.
- The **Local zone** changes are actually phase changes relative to the **Remote zones**, but the existing Grid recording systems incorrectly record these as frequency changes.
- For a stable Grid must limit the value of the **Phase Jump** angle and the **RoCoF** rate in each **Local zone.**

The dynamic power flow in the Grid



- The start is a **Maximum Power Transient "MPT"** in the **Local zone** that gives a **Phase Jump** angle at a time = 1.0 s.
- The **Total Active Power**, which is the **Active Phase Jump Power** plus **Active Inertia Power**, immediately increases equal to the **MPT** to stabilise the Grid in the **Local zone**, see **G4** and this causes the **Local zone RoCoF** rate of -1 Hz / s, see **G1.**
- Each **Remote zone of the Grid** has a lower **RoCoF** rate of typically - 0.25 Hz / s, see **G2.**
- A typical **Remote zone** has a slower and smaller **Total Active Power**, see **G5.**
- The increase in the **Phase Jump** angle between the **Local zone** and the rest of the GB AC Grid causes a large pulse of **Active Infeed Power**, lasting about 1 second into the **Local zone**, see **G3.**
- This causes the **Local zone** frequency to increase and become aligned with the rest of the GB AC Grid, see **G1** and **G2,** and to stop the frequency fall the **Active Frequency Response Power** has to increase in typically 4 seconds, see **G6**.

The power in the Local Zone and the Remote Zones of the GB AC Grid.

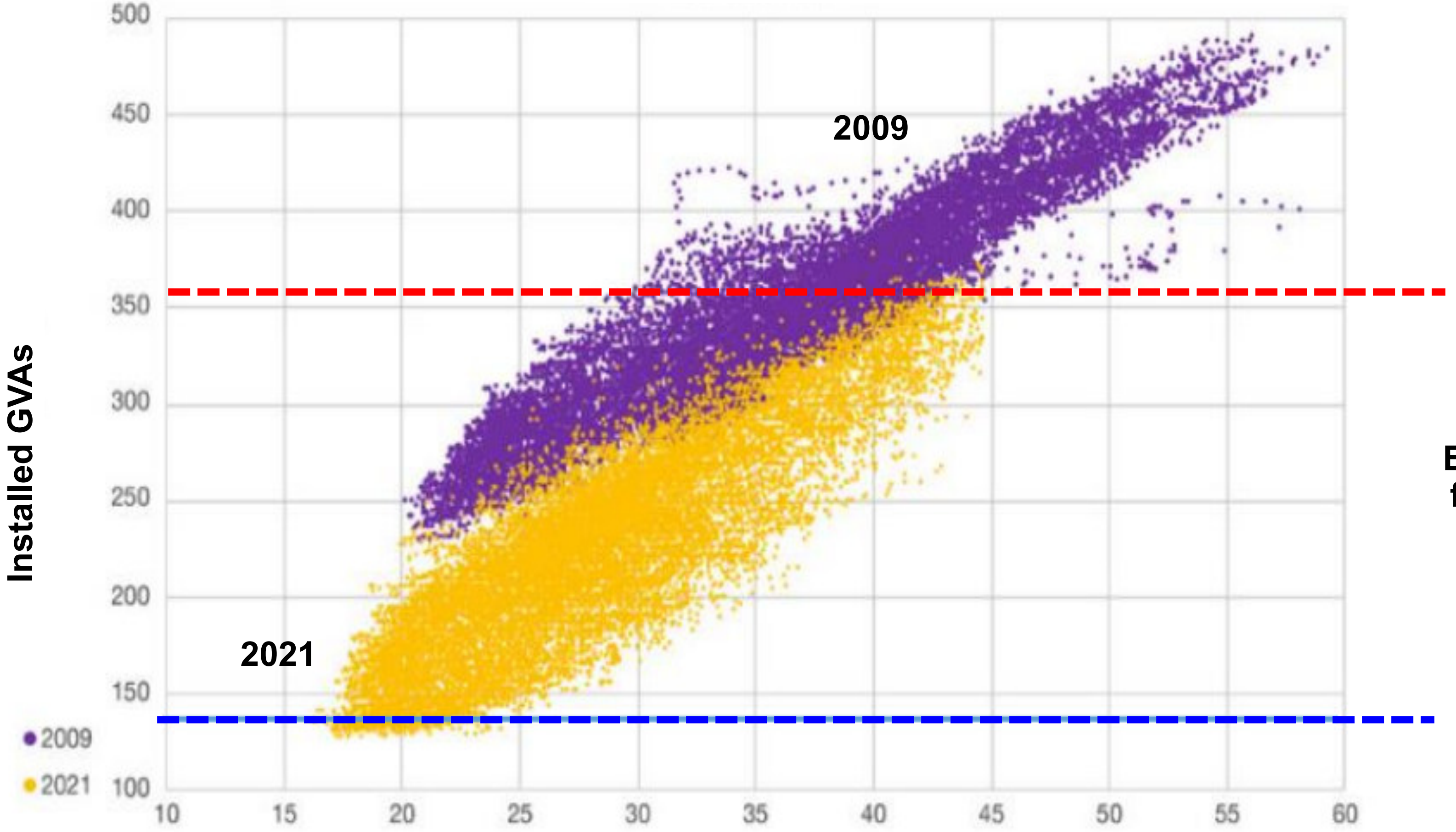


Time in seconds from fault. Image based on data in the NGESO's public domain archives.

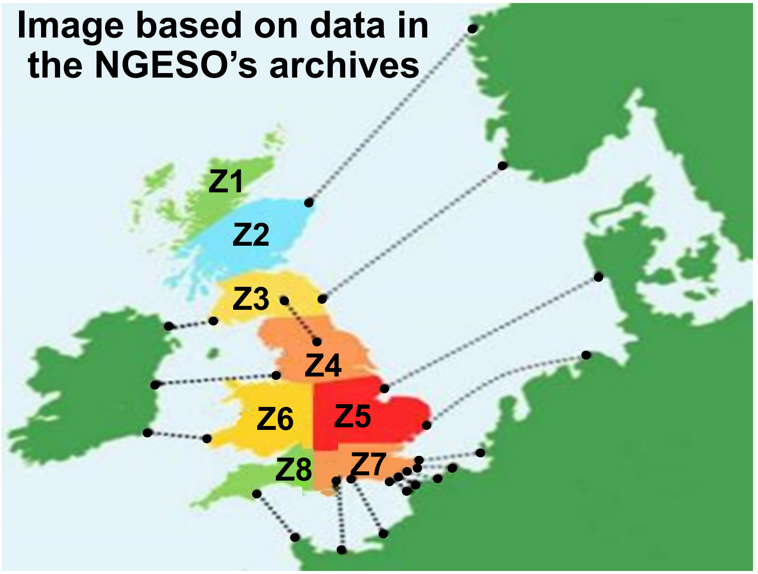
- These are the responses of real 560 MW synchronous generators, 4 at the power transient's location and 2 at remote locations.
- The required **Local Zone's Active Inertia Power** in GW = **(-1 x Installed GWA x RoCoF rate x 2) / (Frequency).**
- The **Remote Zones** are not significantly initially affected by the **Local Zone's** power transient.
- For a **RoCoF** rate of -1 Hz / s the required **Local Zone Installed GWs = (Power transient in GW x 25).**
- For a power transient of 1.8 GW this needs 45 GWs of inertia in each **Local zone** to limit the **RoCoF** rate to +/- 1 Hz / s.
- The +/- 1 Hz / s is the limit for synchronous generators, and it was not measured correctly for this event by the recording system.

The overall levels of inertia required in a future GB AC Grid

2009 versus 2021



Demand in GW based on data supplied by NGESO



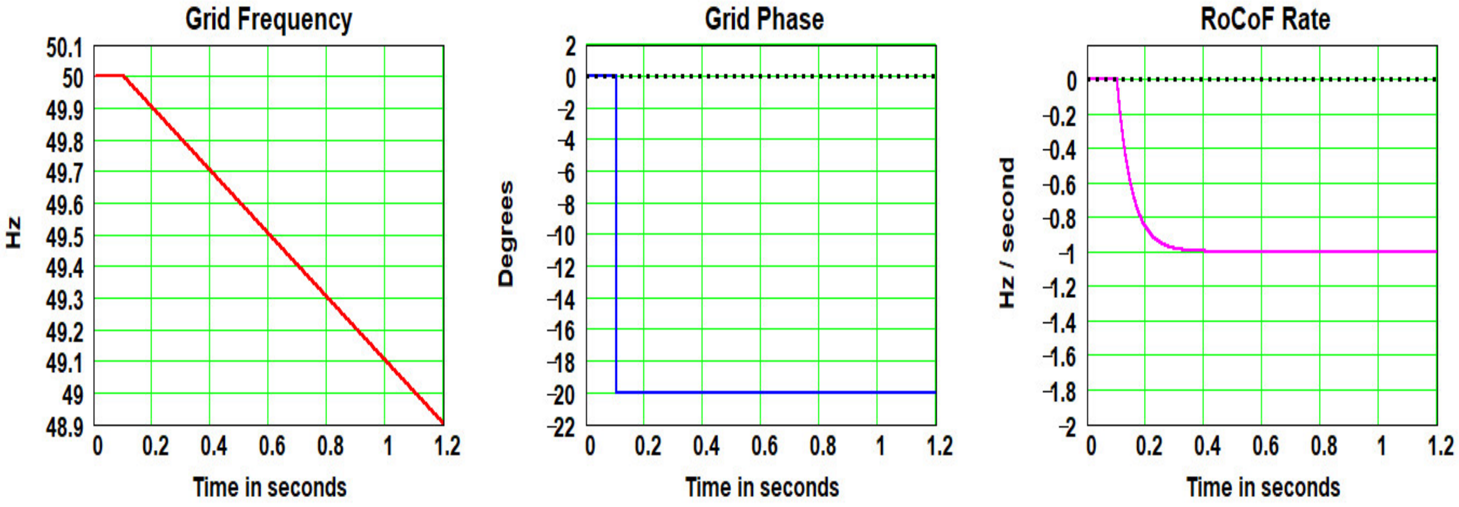
Enstore's prediction for a GB AC Grid with no fossil fuel generators and eight Local Zones.

NGESO's existing minimum Inertia operating policy.

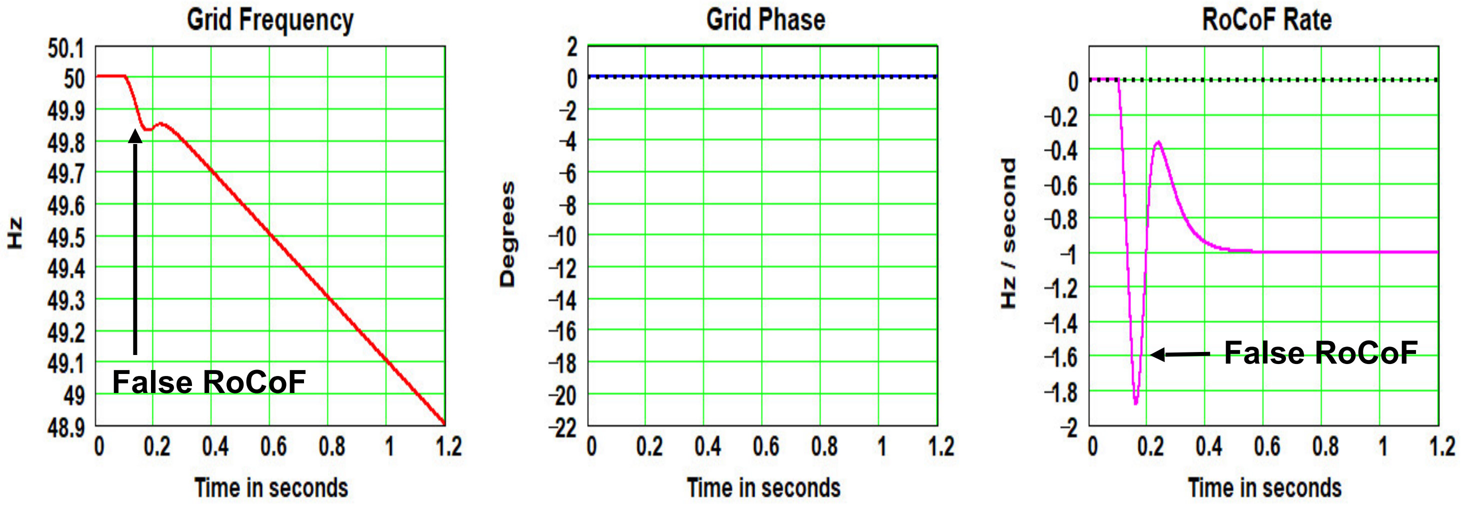
- The graph shows the market-provided inertia.
- The **NGESO's** existing plans are to install 40 GWs of inertia in the near future which is way short of 360 GWs = 8 x 45 GWs.
- This shows that in **Enstore's** opinion that a very significant future investment in extra inertia is needed for a **Stable GB AC Grid**.

Recording Phase Jump Angle values and RoCoF rates

Measured results with the Enstore's algorithms



Measured results with typical existing algorithms



This data is based on an Andrew Roscoe report see:
https://strathprints.strath.ac.uk/61522/

- All the graphs are for a system with a -20 degree **Phase Jump Angle** plus a following **RoCoF** rate of – 1 Hz / s as occurs in a real system.
- The top graphs are the measured results using the **Enstore's** measuring algorithm.
- The lower graphs are the measured results using a typical existing algorithm.
- To avoid incorrect standards and to enable the correct number of **Units** to be installed in a **Local Zone** it is very important that accurate **Phase Jump Angles** and accurate **RoCoF** rates are measured for a power transient, as false **RoCoF** values must be eliminated.
- The GB Grid Code has the definition of improved recording requirements in section **ECC.6.6.1.9.**
- To give accurate results **Enstore** uses a defined test input waveform that produces a defined **Phase Jump Angle** followed by a defined **RoCoF** rate that is available from **Enstore**.

Part 2. The seven possible steps in developing the GB AC Grid

Step 1. A historical GB AC Grid.

Step 2. A present day GB AC Grid.

Step 3. A fully stabilised GB AC Grid.

Step 4. A reliable GB AC Grid.

Step 5. A reliable GB AC Grid with LDES Units.

Step 6. A reliable GB AC Grid with Hydrogen power Units.

Step 7. A reliable GB AC Grid with DDES Units.

Notes:

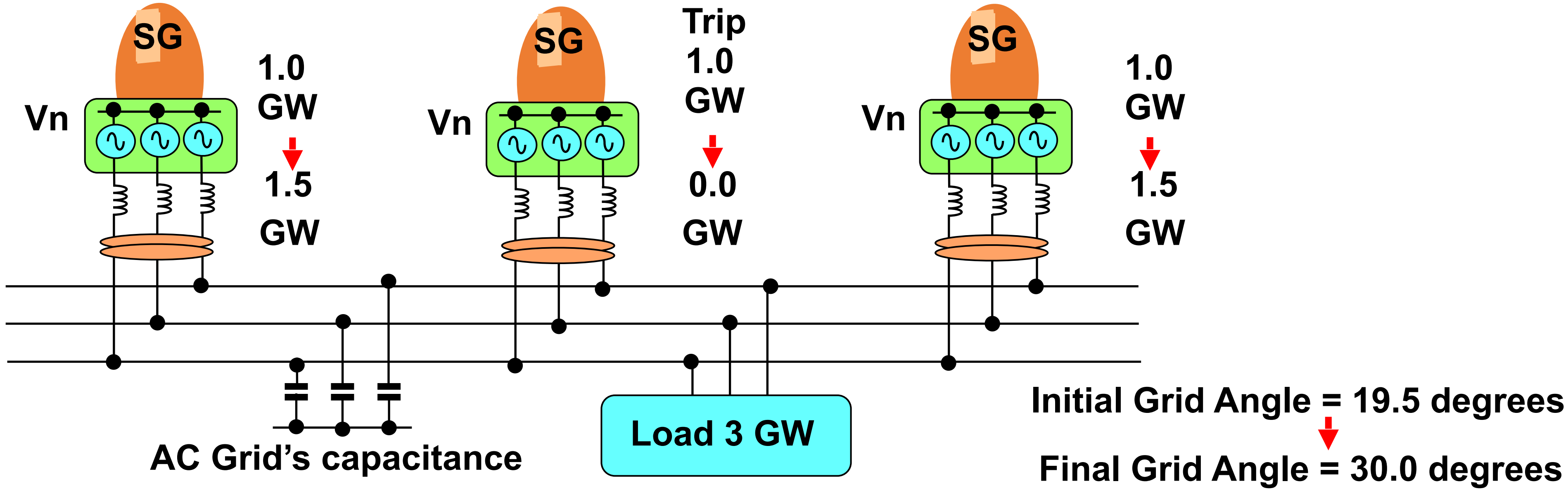
Planning for the long term will avoid installing Units in the short term that do not provide long term benefits.

SDES is Short duration Energy Storage.

LDES is Long duration Energy Storage.

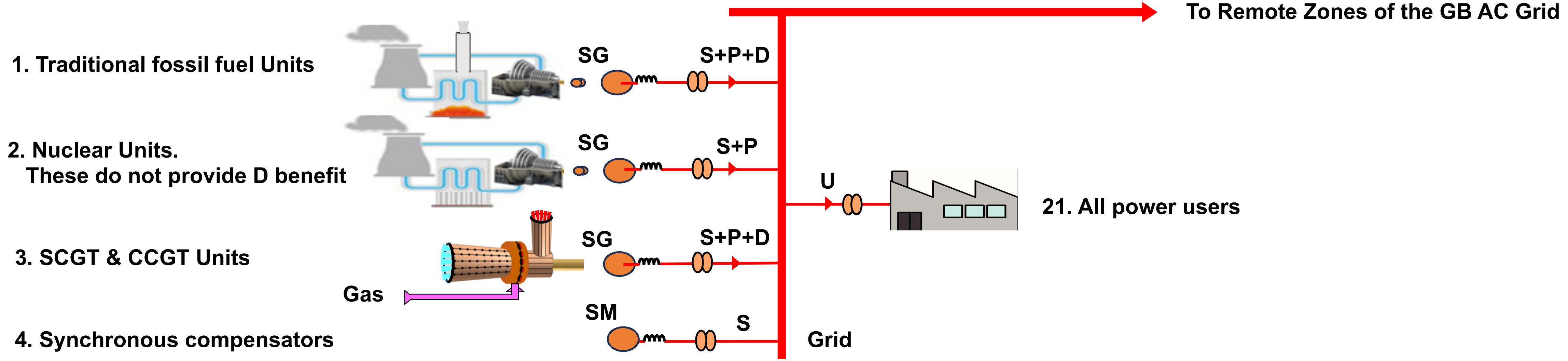
DDES is Dunkelflaute duration Energy Storage.

Active Phase Jump Power and **Active Inertia Power with Synchronous Generators "SG"**



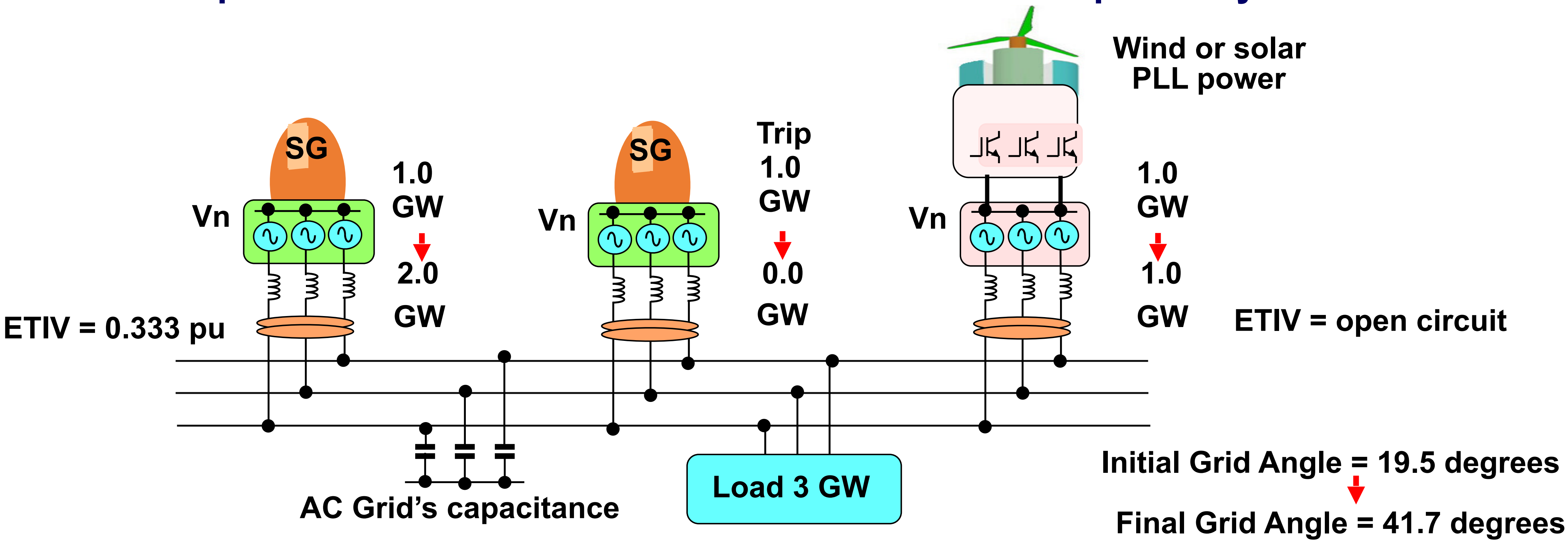
- **For each SGs the AC supply impedance ETIV = 0.333 pu in this presentation.**
- The **Initial Grid Angle** is given by **Asin (Power pu** x **ETIV pu**), = Asin (1.0 x 0.333) = 19.5^0.
- After the power loss the **Grid's Angle** changes very rapidly until the power balance is restored by each **SGs** allowing the instant flow of extra **Active Phase Jump Power** = 0.5 GW to stabilise the change in the **Grid's Angle.**
- The AC supply inductors act like springs, that increase in length, and the **Final Grid angle** = Asin (1.5 x 0.333) = 30.0^0.
- The change is called the Grid's **Phase Jump Angle,** = 10.5^0 degrees, and this happens without any control actions by the **SGs.**
- The power comes from the inertia of the **SGs,** so the AC Grid's frequency starts to fall and the **SGs** then supply power called the **Active Inertia Power** to limit the Rate of Change of Frequency "**RoCoF**" rate with an allowed maximum value of +/- 1 Hz / s.
- The two **SGs** then supply the slow response **Primary Response power** to recover the AC Grid's frequency back to 50 Hz.
- There was no need for a limit on the Grid's maximum **Allowed Phase Jump Angle "APJA"** as **SGs** do not have a **Current Limit**.

Step 1. A historical GB AC Grid



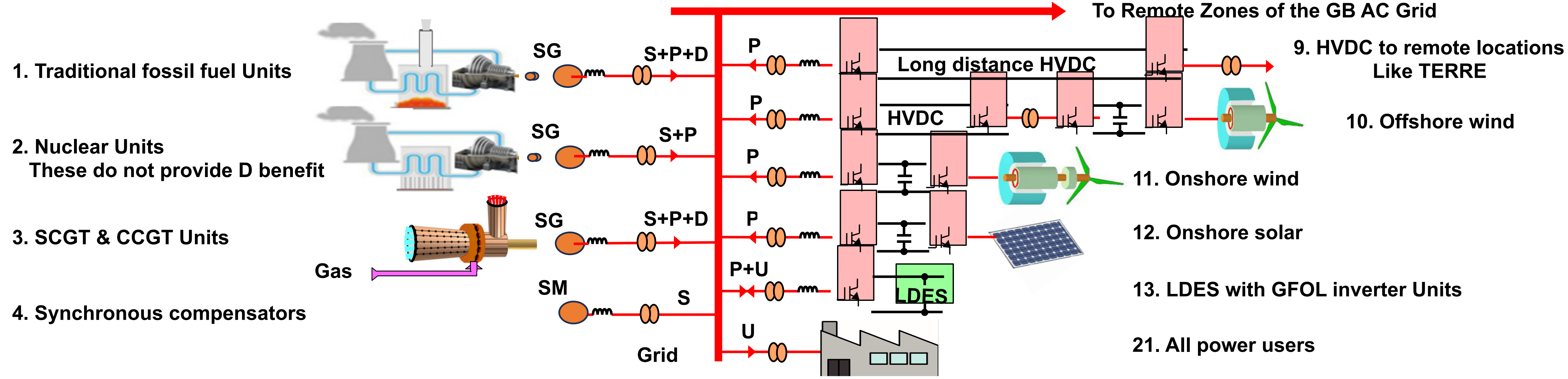
- This is an example of a **Local Zone** of the GB AC Grid that existed before renewable energy Units were installed.
- **SG** is a Synchronous Generator, **SM** is a Synchronous Machine (compensator).
- The slide shows four types of AC power:
  - ➢ **S** is the **Active Phase Jump Power** and **Active Inertia Power** to stabilise the GB AC Grid.
  - ➢ **P** is a Power producer.
  - ➢ **U** is a Power user.
  - ➢ **D** is the ability to provide extra **DDES** power.
- As the **SG** and the **SM** do not have a **Current Limit** there was no need for a limit on the maximum **Allowed Phase Jump Angle**.
- The **Active Phase Jump Power** was not a requirement, as it was essentially supplied for free from Synchronous generators.
- The synchronous compensators were mainly used to supply **Reactive Power.**
- The Nuclear Unit supplies a steady base load and can not increase its output to supply extra **DDES** power.
- The next **Step** was to add renewable wind and solar power using **Grid Following** inverters.

Active Phase Jump Power and Active Inertia Power of a renewable power system



- For the **PLL** power the **ETIV** is effectively an open circuit giving a net **Local zone ETIV** = 0.333 pu after the transient.
- The new angle in the Grid is Asin (2 x 0.333) = 41.7^0 and the **Phase Jump Angle** = 22.2^0 that is twice the value with three **SGs.**
- The following actions are then similar to the slide with three generators, but the loss of the **Active Phase Jump Power from the PLL** inverter and the larger **Phase Jump Angle** gives a **Less Stable GB AC Grid.**
- The lower inertia also gives an increased **RoCoF** rate, due to the reduction in the **Active Inertia Power,** and a **Less Stable Grid.**
- This problem is increasing as **PLL** based renewable power Units are replacing rotating synchronous generator power Units.

Step 2. A present day GB AC Grid



- This is an example of a **Local Zone** of the GB AC Grid with renewable power Units using **Grid Following** inverters and **HVDC**.
- The **GFOL** inverters are shown in pink.
- The **LDES** Unit is typically rated to have a 1 second power response with a typical power duration of more than 1 hour.
- The **LDES** Units are normally used to control the AC Grid's frequency.
- As the renewable power Units replace the synchronous generators the AC Grid's **Phase Jump Angle** and the **RoCoF** rate increase, for a power transient, giving a **Less Stable GB AC Grid.**
- This can result in extra synchronous generators having to be run on line, compared with the number needed to supply the GB AC Grid's power demand.
- The renewable power generators are then unable to supply all the available renewable power and are paid constraint payments.
- The next **Step** is to add the appropriate Units to stabilise the GB AC Grid.
- This will make it possible to install extra renewable power Units and to use all the available renewable power.

Step 3. A fully stabilised GB AC Grid

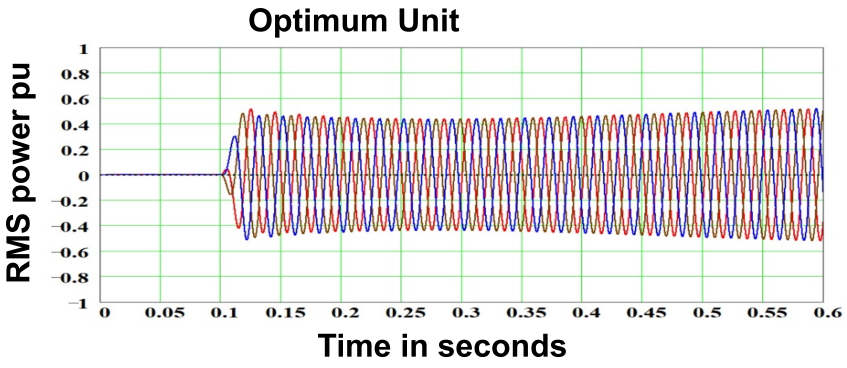
The required actions to stabilise a local zone of the GB AC Grid

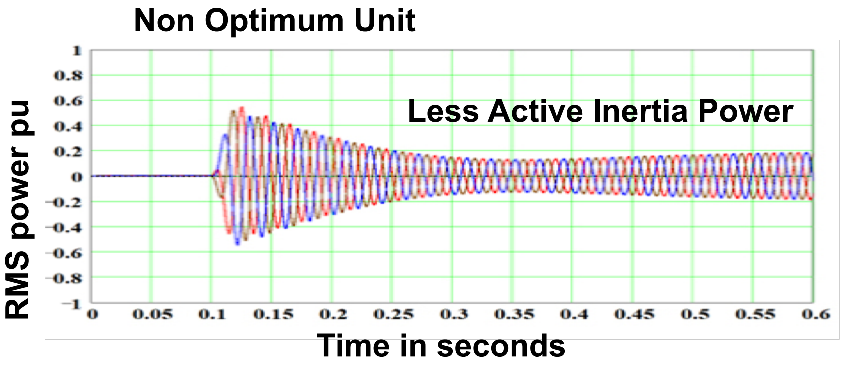
The following two items must be provided by the connected Units when the defined Maximum Power transient "**MPT**" occurs in each **Local Zone** of the GB AC Grid:

- A level of **Active Phase Jump Power** equal to the **MPT** that is presently set at 1.8 GW.
  The **Active Phase Jump Power** of a **Unit** is given by **Sine (Allowed Phase Jump Angle "APJA") / ETIV .**
  For an **APJA** of 20 degrees and an **ETIV** = 0.333 this gives an **Active Phase Jump Power** of = 1.0 pu.

- A level of **Active Inertia Power** equal to the **MPT**.
  The **Active Inertia Power** of a **Unit** for a **RoCoF** of 1 Hz / s is given by **- H / 25.** The 1 Hz /s is the limit for synchronous Units.
  For a high inertia Unit with **H = 12.5** this gives an **Active Inertia Power** of = 0.5 pu.

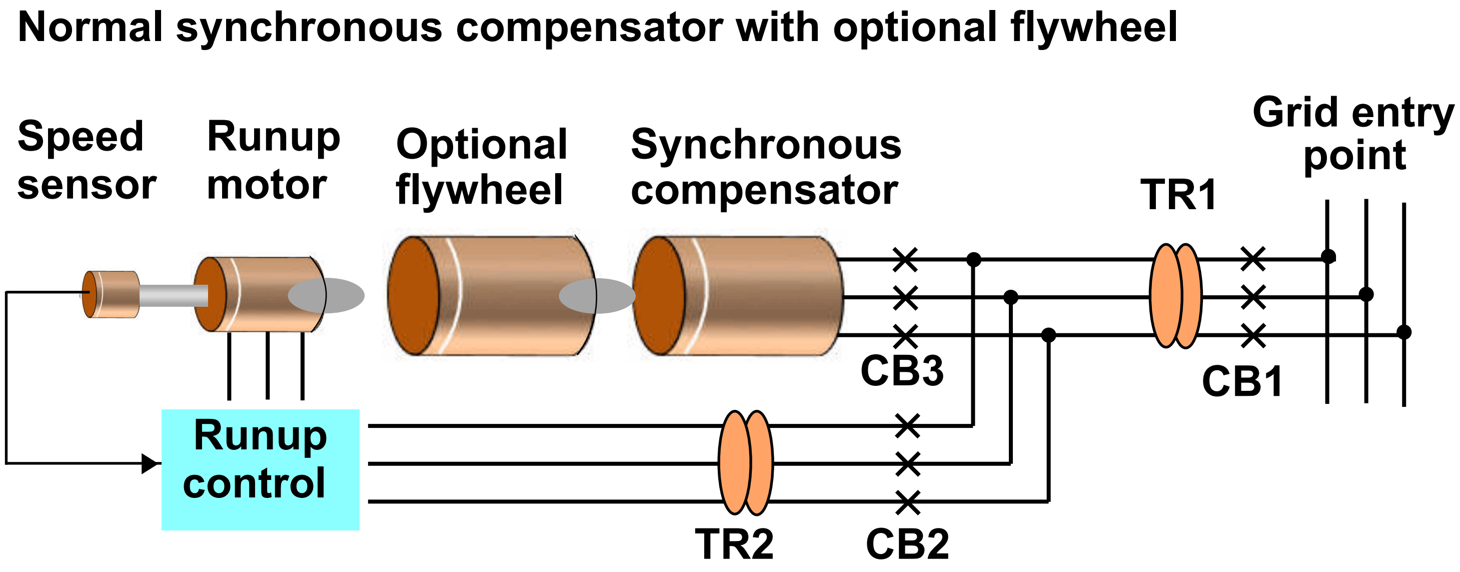
The response of a Unit is shown below and as most Units are a **Non Optimum Units** this tends to give an oversupply of **Active Phase Jump Power.**





- Based on this data an initial study by **Enstore,** and data from **Cenelec,** gave a maximum value for the **APJA** of 20 degrees.
- A realistic GB AC Grid will use a combination of all types of **Units,** and allowing for the oversupply of **Active Phase Jump Power,** is the reason for the **Enstore's** latest proposed maximum **APJA** of 12 degrees.

Synchronous compensators



- The Runup control starts the Unit until the compensator is connected to the Grid by **CB1 + CB3.**
- Synchronous compensators deliver a high level of **Active Phase Jump Power** but have a lower **H** value, compared with synchronous generator power Units, so they only deliver a low value of **Active Inertia power.**
- An added flywheel is now an available option to raise the **H** value, but the added mass may give:
  - ➢ A low level of active power damping with a low value of AC power **Damping Factor.**
  - ➢ A shaft resonance with very low damping that may result in either failures and or AC Grid resonance problems.

Synchronous compensator with added flywheel

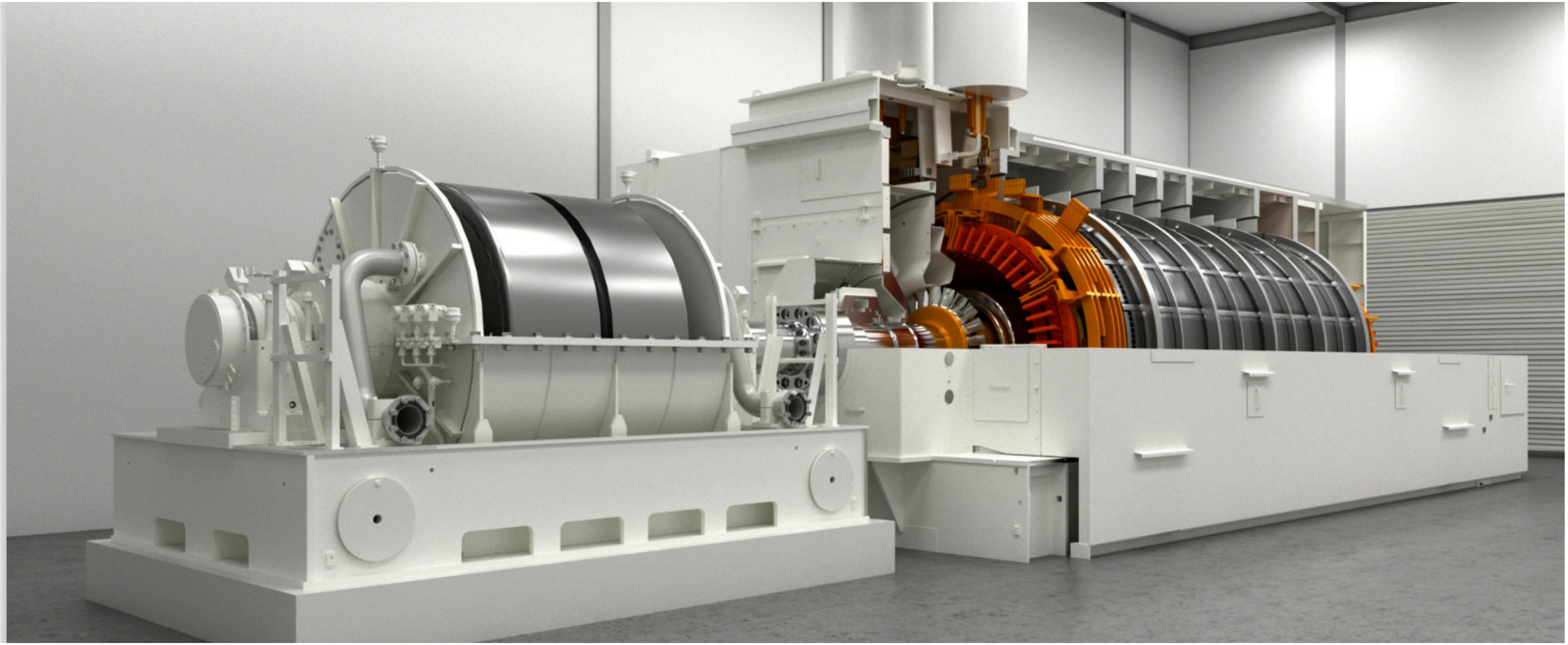
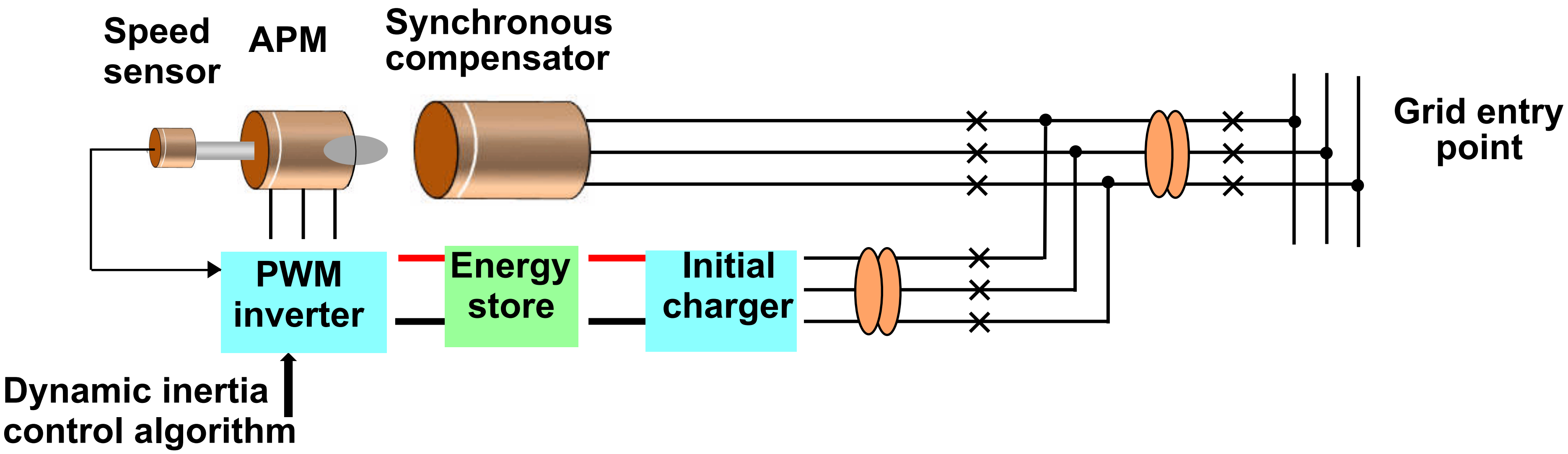


Image provided by Siemens Energy from the GridStabilityBrochureApril2023-pdf.

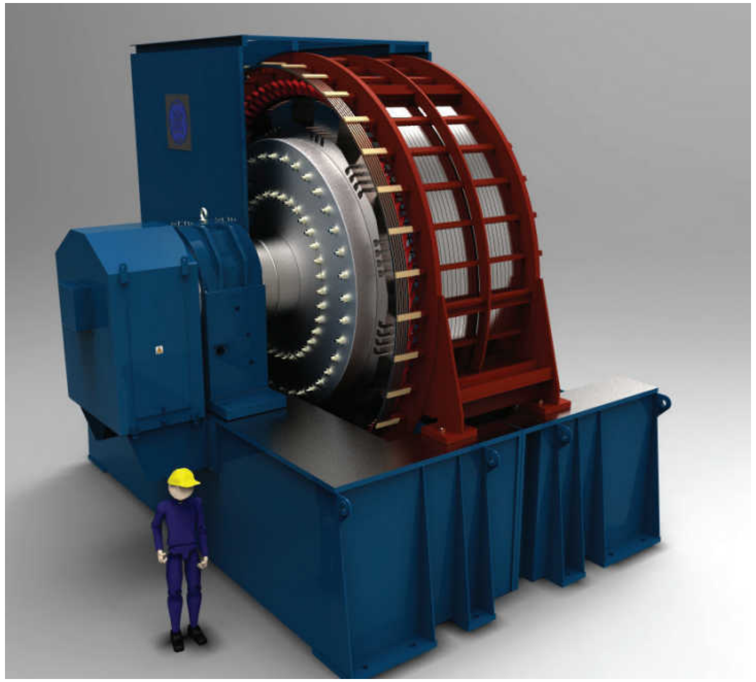
For stabilising the GB AC Grid the use of Units with a high inertia is essential to provide extra **Active Inertia Power.**
A flywheel can increase the inertia of a generator to 4000 MW.s.

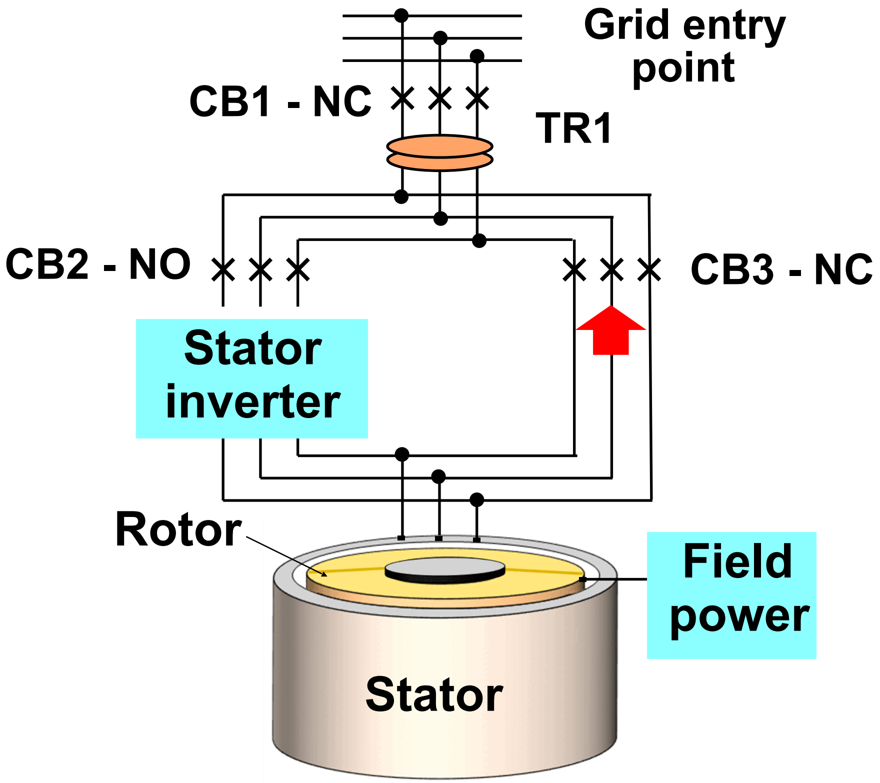
Advance synchronous compensators with an Auxiliary Power Motor “APM”



- This circuit replaces the run up motor with an Auxiliary Power Motor “**APM**“ that can:
  - ➢ Increase the **H** value by a factor by typically 5:1 to give extra **Active Inertia Power**.
  - ➢ Avoid the resonant modes that may occur with added flywheels.
  - ➢ Provide a 0.7 AC power **Damping Factor** or even higher.
  - ➢ The Unit uses a fully industrially proven **Dynamic inertia control algorithm** that increases the Unit’s **H** value without any need for any sensors connected to the Grid.
- The **APM** operates for short time periods, that enables a high **APM** overload rating to be used, and also avoids a shaft resonance by using a phase locked vector control system.
- The circuit also assists in the recovery of the Grid by supplying **Active Control Based Damping power** as an **ESS** Unit.
- The initial charger is only needed to start the run up. The energy store can be recharged via the inverter and compensator.
- **This needs a pilot project** to validate this technology in the GB AC Grid that has been proven in industrial systems.

The high inertia synchronous compensator



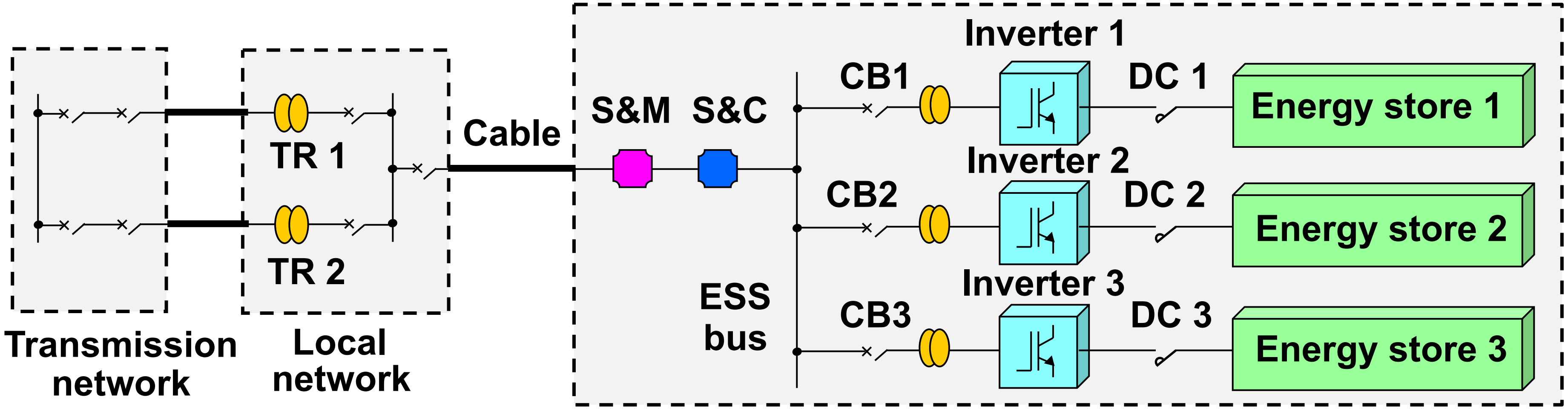


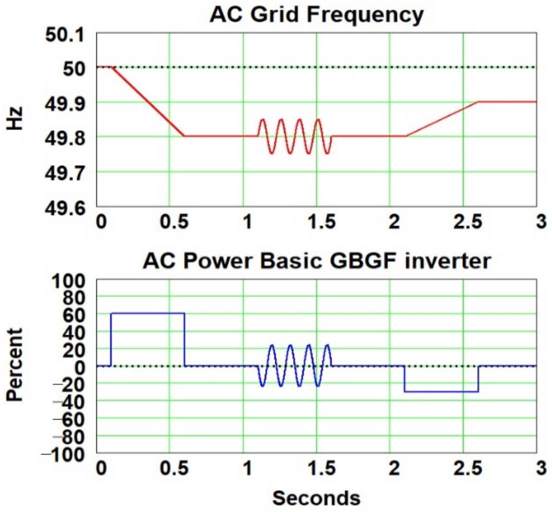
Units available with horizontal or vertical rotors.
The Unit shown is the Statkraft Keith 2022 compensator reproduced by permission of GE Power Conversion.

- The high inertia synchronous machine is normally directly on line, with **CB2** open, to allow the flow of **Active Phase Jump Power** plus supply **Active Inertia Power** and **Active Damping Power** with ratings up to 200 MVAR and 2.115 GWs.
- When a power transient occurs this stabilises the Grid just like a synchronous compensator but with a high **H** value.
- When the frequency of the Grid is recovering the **CB3** is opened and the **CB2** is closed.
- The Unit is then acting as an Energy Storage Unit to supply **Active Control Based Power** that can help the Grid recover as well as adding **Active Damping Power**.

The design of an Optimum Basic GBGF inverter

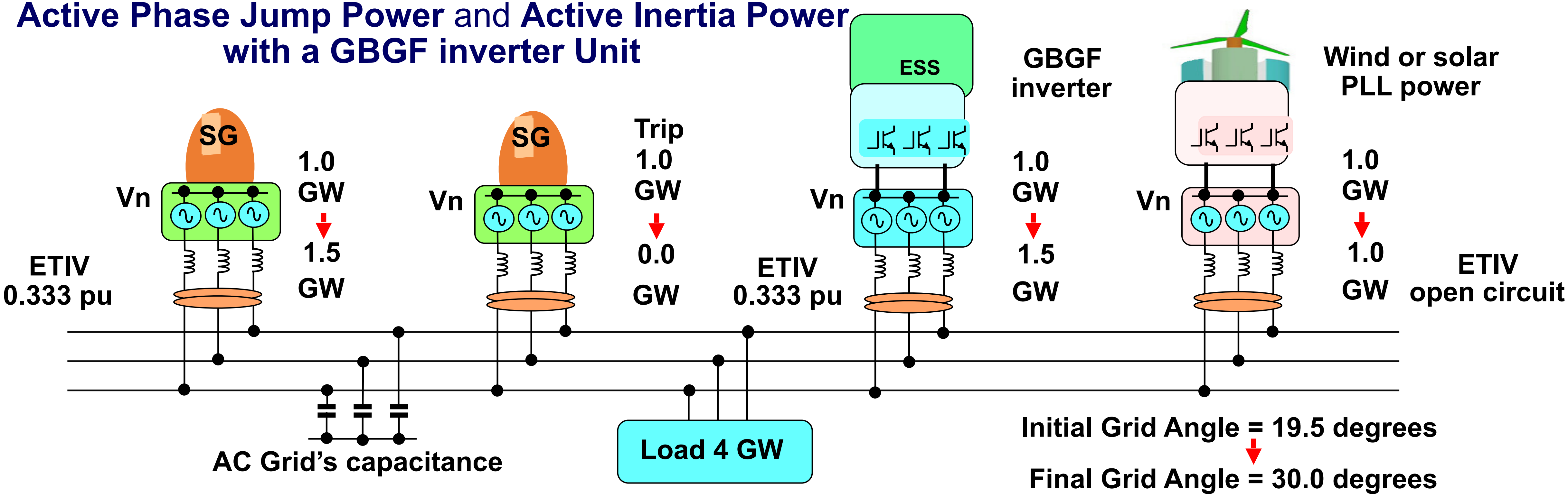
S & M = Sensors and Monitoring. S & C = Sensors and Control





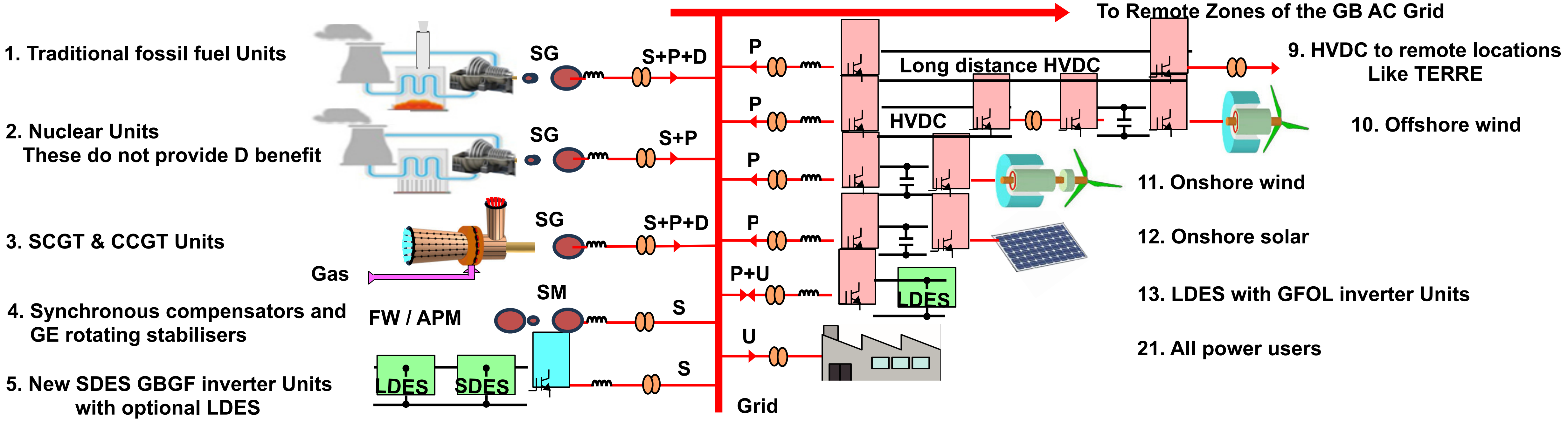
- A typical **Basic GBGF** inverter uses many identical **GBGF** inverters in parallel to provide redundancy and high availability that instantly allows the flow of **Active Phase Jump Power** for any GB AC Grid power transient.
- A **Basic GBGF** inverter only responds to changes in the AC Grid's frequency and cannot have **Droop Control** as this would rapidly empty its **ESS**, but it does supply **Active Inertia Power** and **Active Damping power.**
- The delivered energy comes from the Energy stores that is approximately 20 % of the energy of an equivalent **SG,** but larger energy stores can be used to provide an **ESS GBGF** inverter with **Droop Control** and a higher **Peak Current Limit.**
- An optimal design of a **Basic GBGF** inverter has a **Phase Jump Angle Limit** value of 12 degrees to allow the flow of **Active Phase Jump Power** with a value of 0.6 pu plus a **Peak Current Limit** of 1.1 pu to allow for point on wave switching transients.
- This Unit has the **PJAL** equal to the proposed **APJA** so it stays in the **Normal Mode** for power transients.
- It also has an **H** = 12.5 value with a Unit's resonant frequency of approximately 1 Hz to also supply an **Active Inertia Power** of 0.6 pu for a **RoCoF** rate of 1 Hz / s giving an Optimum Unit.
- Installing the **Active Phase Jump Power** & **Active Inertia Power** from one inverter is the lower cost solution when compared with doing this from separate inverters, as proposed by some standards, that would need twice the installed inverter rating.

Active Phase Jump Power and **Active Inertia Power with a GBGF inverter Unit**



- For the **GBGF** inverter the **ETIV** is 0.333 pu and the new angle in the Grid is Asin (1.5 x 0.333) = 30.0^0 .
- The **Phase Jump Angle** = 10.5^0 that is the same value with three **SGs.**
- The actions are then similar to the slide with three generators for the **Active Phase Jump Power** and the **Active Inertia Power.**
- The Grid's stability is the same, which is why the **GBGF** inverters were developed to operate like synchronous machines.
- To rate the **GBGF** inverter's **Current Limit** requires the following to be defined in a proposed future Grid Code and **SQSS** update:
  - ➢That the inverter designer can set the **Phase Jump Angle Limit "PJAL"** to define the Unit's rated **Active Phase Jump Power.**
  - ➢That the AC Grid's maximum **Allowed Phase Jump Angle** is defined in the **SQSS**. The **Enstore** proposal is 12^0.
  - ➢That a proposed **Type Test** is used to show that the rated **Active Phase Jump Power** is delivered for AC Grid **Phase Jump Angle** transients from the **PJAL** angle up to the **APJA** angle, this is to validate that a **GBGF** inverter has a reliable response.

Step 3. A fully stabilised GB AC Grid



- This is an example of a **Local Zone** of the GB AC Grid that is fully stabilised.
- The new synchronous compensators either have Flywheels “**FW**” to add inertia or extra synthetic inertia added by an **APM**.
- The GE rotating stabilisers are also used to add controlled AC Grid stability.
- The **GBGF** inverters are shown in blue that provide the **SDES** and some **LDES**.
- For an **MPT** the **SDES** Units allow the instant flow of **Active Phase Jump Power** for a very short time to stabilise the GB AC Grid and the **GBGF** inverters then immediately supply the **Active Inertia Power** to limit the **RoCoF** rate.
- The GB AC Grid is now able to accept unlimited renewable power normally supplied by **GFOL** inverters.
- A limited number of **GFOL** Units with **LDES** are also being installed to help to control the daily power variations.
- The next **Step** is to have totally reliable power generation.

The proposed essential requirements to have a reliable GB AC Grid

The **MPT** is defined in the **SQSS** for both polarities

Cascade trips are eliminated

The **GBGF** Grid Code is fully updated

The number of **Local Zones** are defined and the correct Units installed

The correct **EMT** model is used to define the **GBGF** inverter's **Current Limits**

A value for the **APJA** is defined plus its **Rise Time**

The **Dual Current Limit** control is implemented

All **GFOL** and **GBGF** inverters are **Type Tested** to the **APJA**

The **GBGF Normal** and **Withstand Modes** are developed

Power reserves are held for at least two **MPT** events

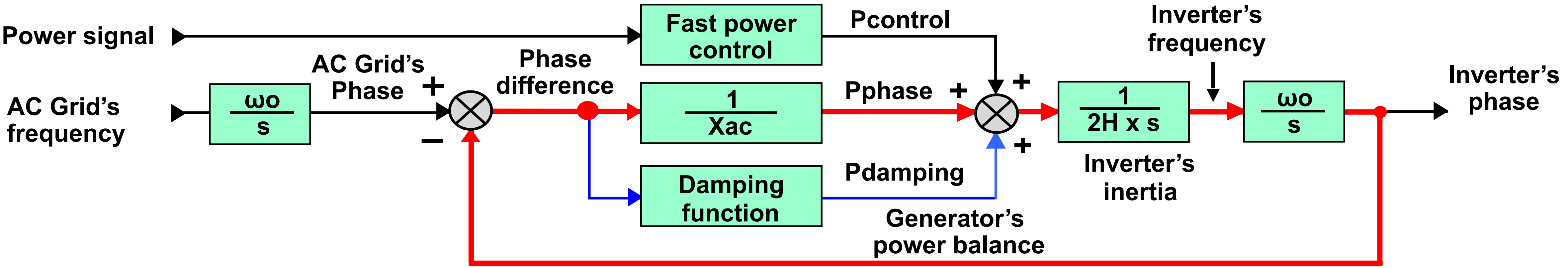
The **Basic GBGF** and **ESS GBGF** inverters are developed

Most power transient take longer than 20 ms to avoid DC components

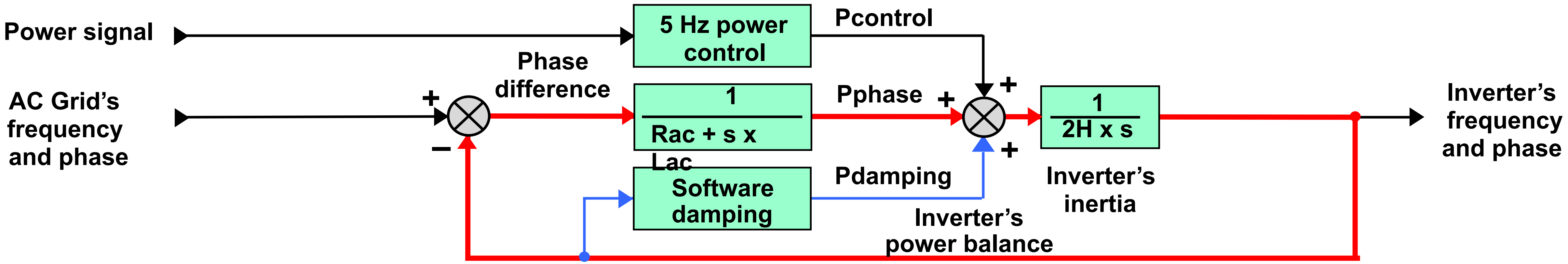
Have **Active Phase Jump Power** and **Active Inertia Power** equal to **MPT** installed in each **Local Zone**

NGESO rewards **Active Phase Jump Power** & **Active Damping Power**

Calculating the Peak Current Limit of a GBGF inverter



- This model of a **GBGF** inverter is derived from the model of a synchronous generator with phase being the integral of frequency.
- This has the function **1 / Xac** for the impedance of the AC supply and for an AC supply **Phase Jump Angle** the power **Pphase** has an instant step which is a wrong result. This model gives good results in the frequency domain but not for **EMT** simulations.

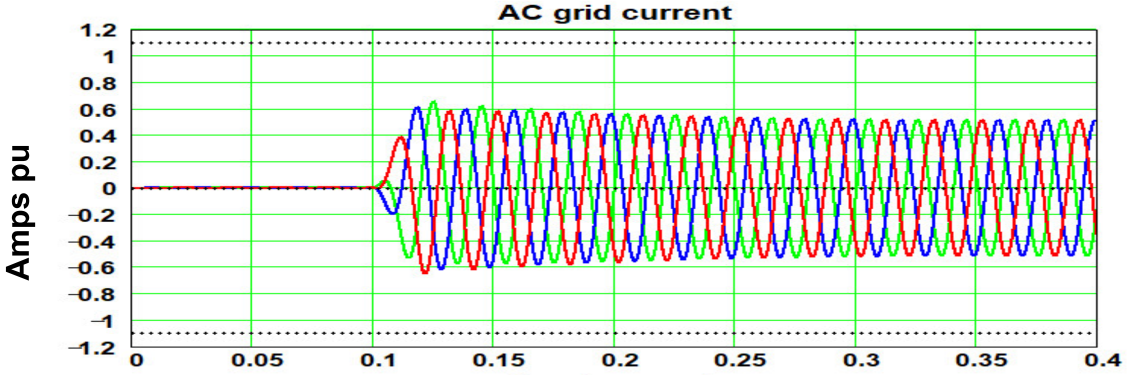


- This is the **Enstore's** model of a **GBGF** inverter and in this model the inverter's phase can change independently of frequency.
- This model uses the function **Rac + s x Lac** for the impedance of the AC supply and for an AC supply **Phase Jump Angle** the power **Pphase** has the correct **di/dt.** This model gives good results in the frequency domain and for **EMT** simulations and can provide a high value of the system's **Damping Factor** from the **Software damping**.
- The two models give identical **NFP** and Bode plots in the frequency domain.

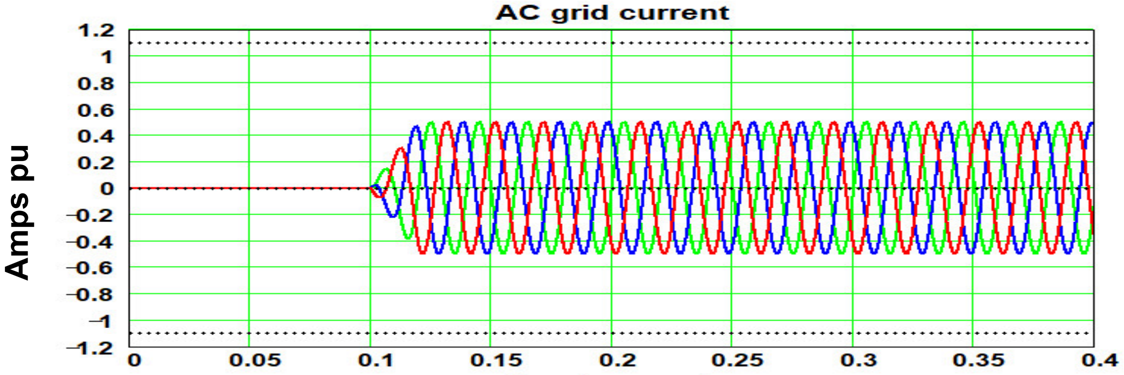
The GBGF inverter’s Peak Current Limit for an AC Grid Phase Jump Angle and RoCoF

- For these simulations the common AC supply input has a 12 degree **Phase Jump Angle** followed by a -1 Hz / s **RoCoF** and the Unit’s parameters are **H** = 12.5 and **ETIV** = 0.333.

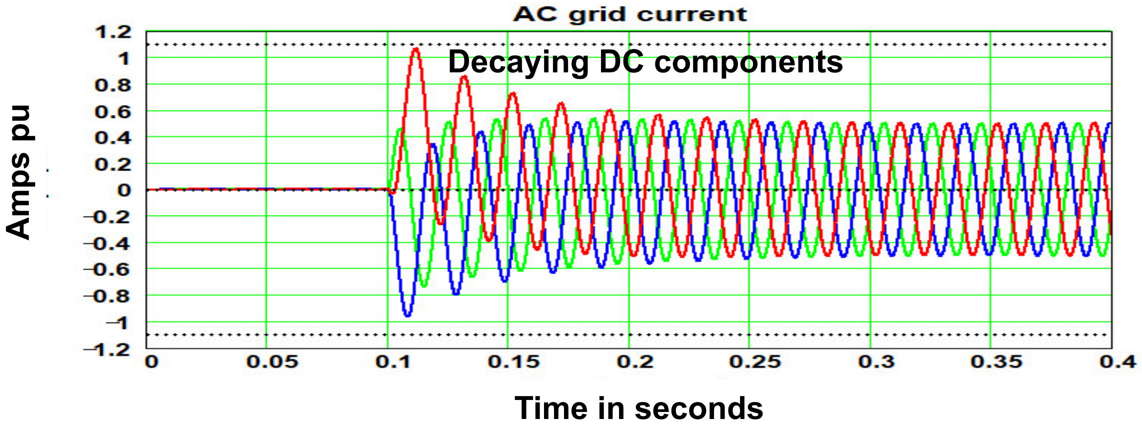
Enstore model with Phase Jump Rise Time 20 ms.



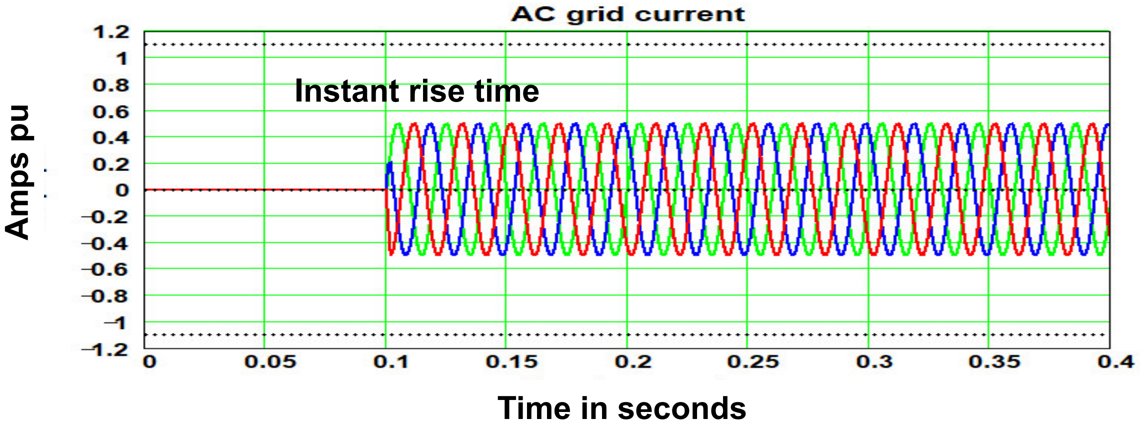
Original model with Phase Jump Rise Time 20 ms.



Enstore model with Phase Jump Rise Time 2 ms.

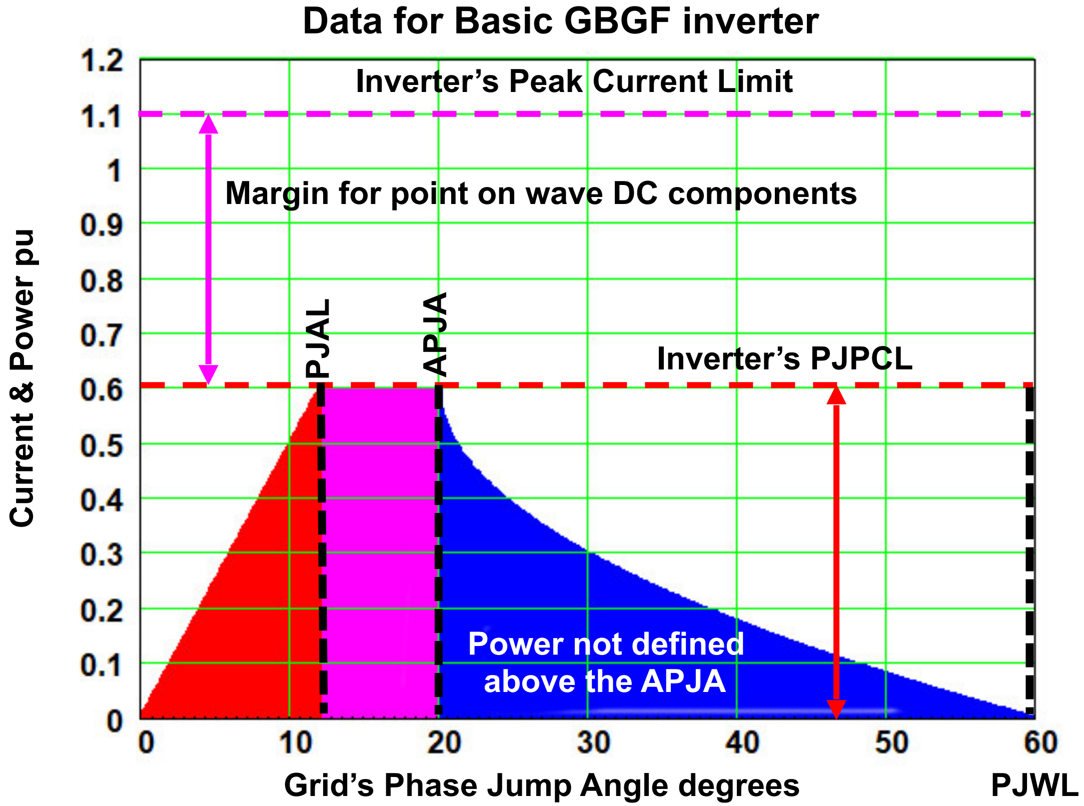


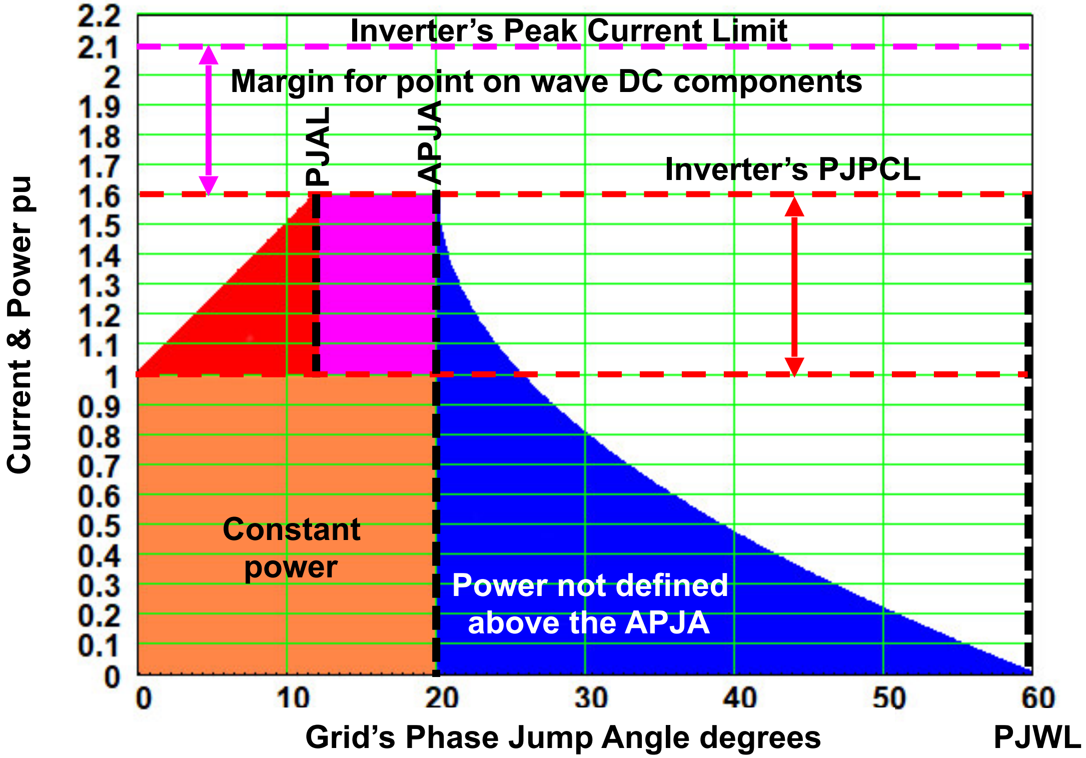
Original model with Phase Jump Rise Time 2 ms.



- The original model is the existing **GBGF** model based on synchronous generators with the AC supply modelled as an impedance.
- The **Enstore** model has the AC supply modelled as a resistance plus inductance to give the correct rate of rise of current and the correct **Peak Current Limit** value for an AC Grid **Phase Jump Angle** with a fast **Rise Time.**
- This is why a large **Peak Current Limit** margin is needed for **Active Phase Jump Power.**

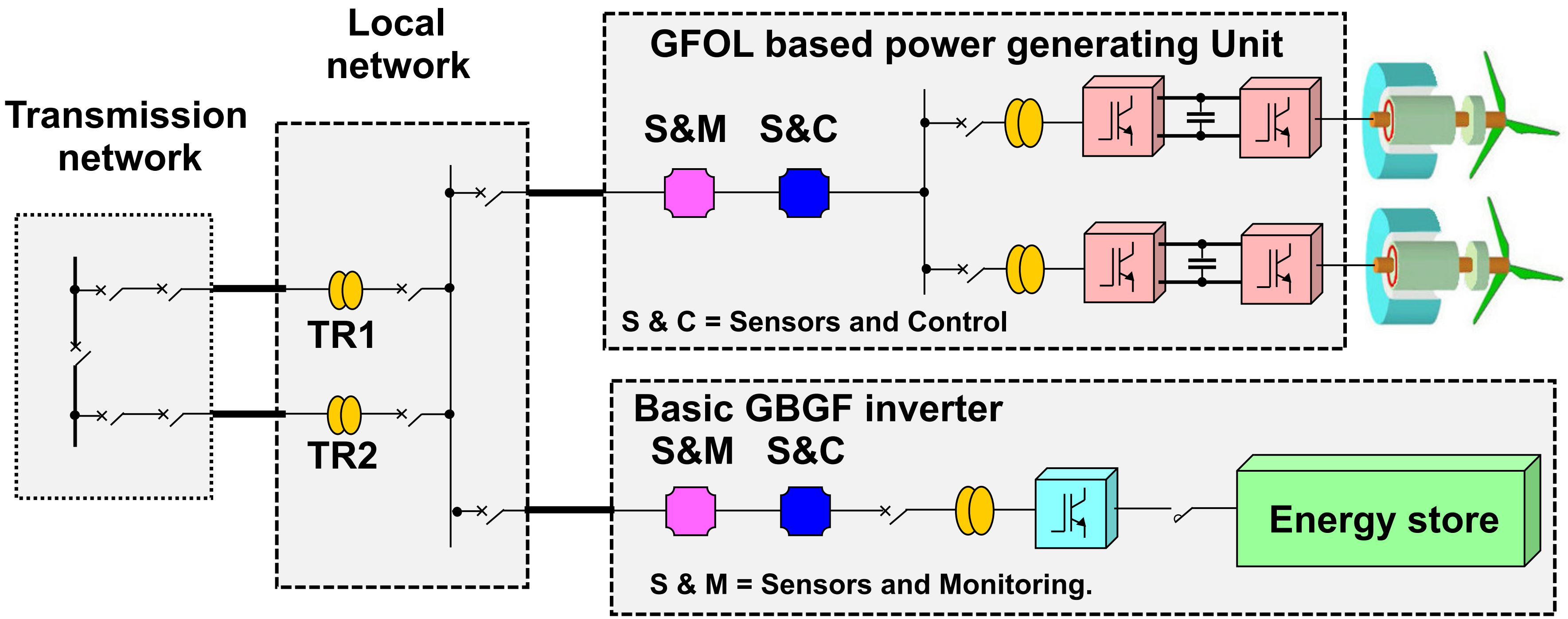
The GBGF inverter's two Current Limits



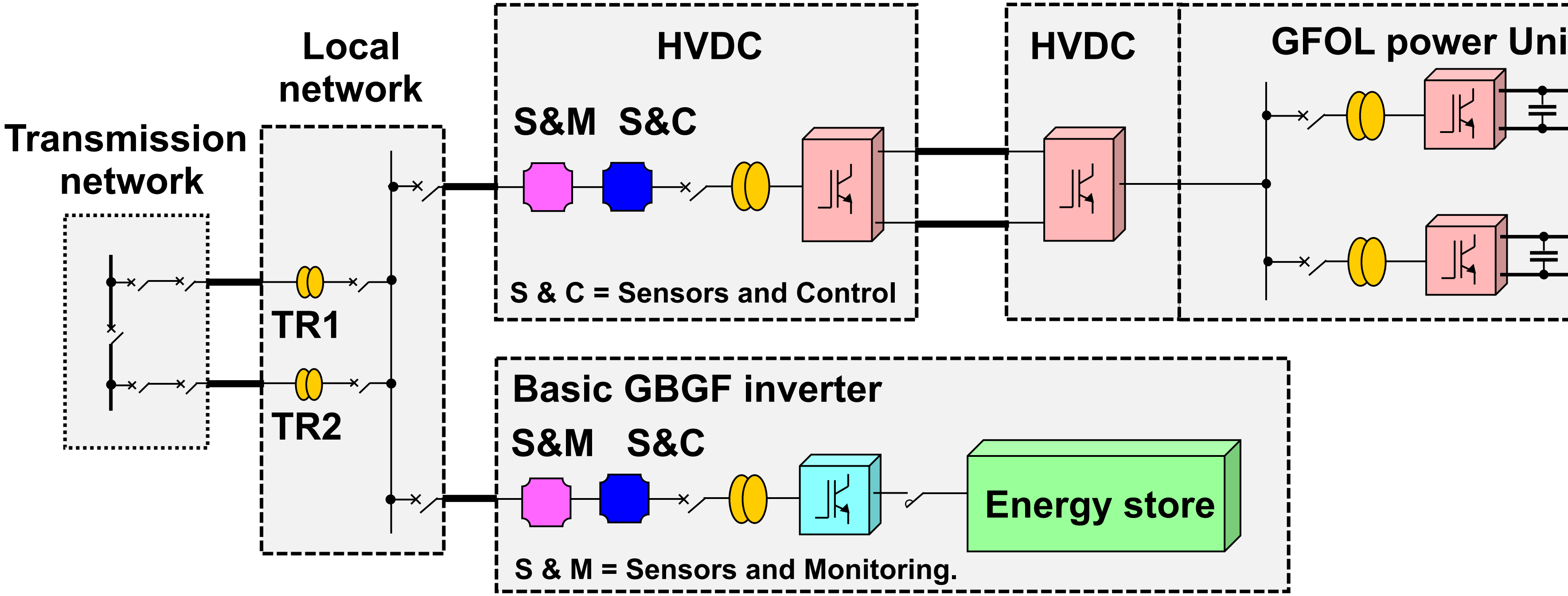


- **PJAL** = **Phase Jump Angle Limit** = Set by the supplier to define the rated **Active Phase Jump Power,** shown as 12⁰.
- **APJA** = **Allowed Phase Jump Angle** = Maximum **NGESO** allowed **Phase Jump Angle** in the GB AC Grid, shown as 20⁰.
- **PJWL** = **Phase Jump Withstand Limit** = can occur when closing a feeder on to a powered GB AC Grid = Up to 60⁰.
- The Left Hand graph is a **Basic GBGF** inverter with no steady output power and the Right graph is a **ESS GBGF** inverter with a **Constant power** rating shown in orange. This graph can be used by renewable power Units operating below their rated output.
- The **Inverter's Phase Jump Power Current Limit "PJPCL"** is needed to limit the **Active Phase Jump power** above the **Constant power** rating to provide a reliable power up to the **APJA** and then without tripping up to the **PJWL.**
- The **Inverter's Peak Current Limit** is needed to protect the inverter for other conditions like a GB AC Grid short circuit fault.

The design of a reliable onshore renewable energy Unit with a Grid stabalising ability

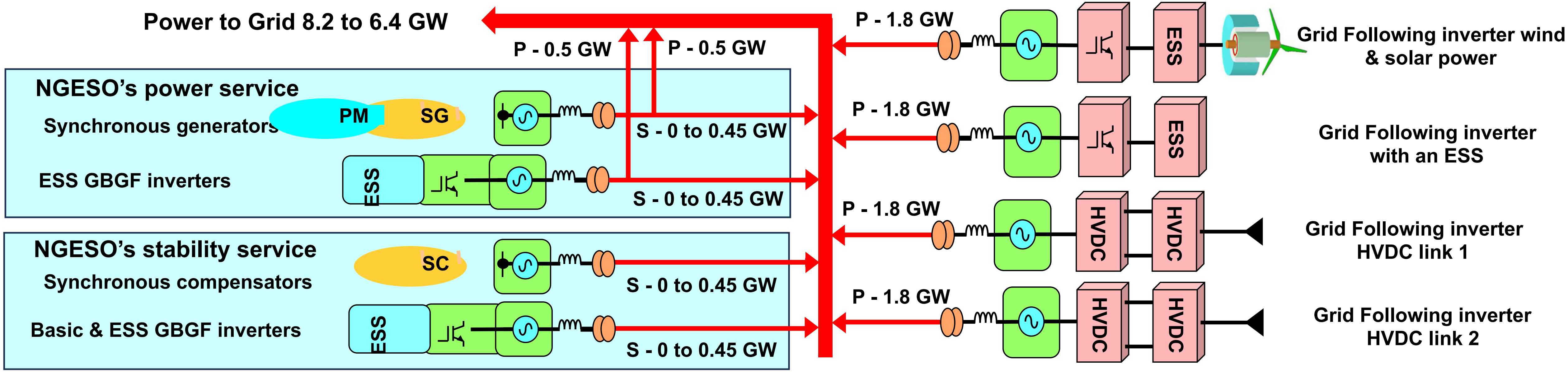


- It is proposed that all existing and new onshore renewable energy Units should be **Type Tested** to operate reliably up to the **Allowed Phase Jump Angle.**
- The use of a **GFOL HVDC** link will then provide a source of reliable power into a stabilised GB AC Grid.
- These wind turbines use a geared drive that can either be, but not limited to, **Active Front End** "**AFE**" inverter Units and **Dual Fed Induction Generator** "**DFIG**" Units provided they meet the GB Grid Code specification and pass the proposed **Type Test.**
- With the correct control system and rating they can have a **GBGF** stabalising ability when operating below rated power.
- If required the **GFOL** inverters can provide a Unit with a Grid stabalising ability by adding the parallel **Basic GBGF** inverter.



- It is proposed that all existing new Units should be **Type Tested** to operate reliably up to the **Allowed Phase Jump Angle.**
- The use of a **GFOL HVDC** link will then provide a source of reliable power into a stabilised GB AC Grid.
- If required the **GFOL HVDC** links can provide a Unit with a Grid stabalising ability by adding the parallel **Basic GBGF** inverter.
- This is important for offshore power as the **Basic GBGF** inverter is only required at the land side end of the **HVDC** Unit.
- The **Basic GBGF** inverter should not be integrated into the **HVDC** link, so that the **Basic GBGF** inverter can provide Grid stability following a trip of the **HVDC** link.
- The wind turbines shown use Direct Drive gearless wind turbines with **GFOL** inverters.

The design of a reliable Local Zone of the GB AC Grid for an MPT = 1.8 GW



This is what needs to happen in each **Local zone** to provide a **Stable AC Grid** when any one of the four **GFOL power Units** trips:

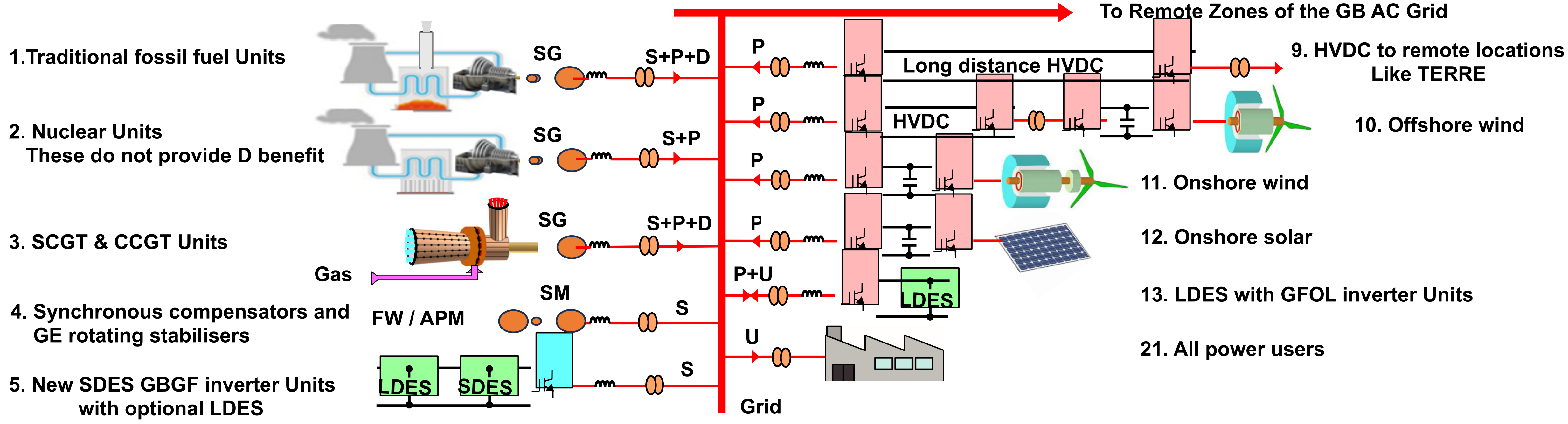
- The local **NGESO's** power plus stability services allow the flow of instant **Active Phase Jump Power,** equal to the **MPT** for about 1 second, to limit the Grid's **Phase Jump Angle** to less than the **Allowed Phase Jump Angle** defined in the **SQSS**.
- The local **NGESO's** power plus stability services, a mix of synchronous machines and **GBGF** inverters, then supplies **Active Inertia Power,** also equal to the **MPT** for several seconds, to limit the **Local RoCoF** rate to 1 Hz / s with the correct polarity.
- Other Grid generators, in all the Grid **Remote zones,** then respond in several seconds to supply an extra value of **Primary Response Power,** equal to the **MPT** to further limit the Grid's **RoCoF** rate and to eventually stop the fall in the Grid's frequency.

If the **NGESO's Local** stability service does not provide the required **MPT** rating the Grid's **Phase Jump Angle** could rise to a very large value causing all the four **Power Systems** to trip giving a power loss of 7.2 GW, that could lead to a total Grid shutdown.

This is why all significant **GBGF** and **GFOL** Power and Stability Units must be **Type Tested** to work reliably up to the **APJA.**

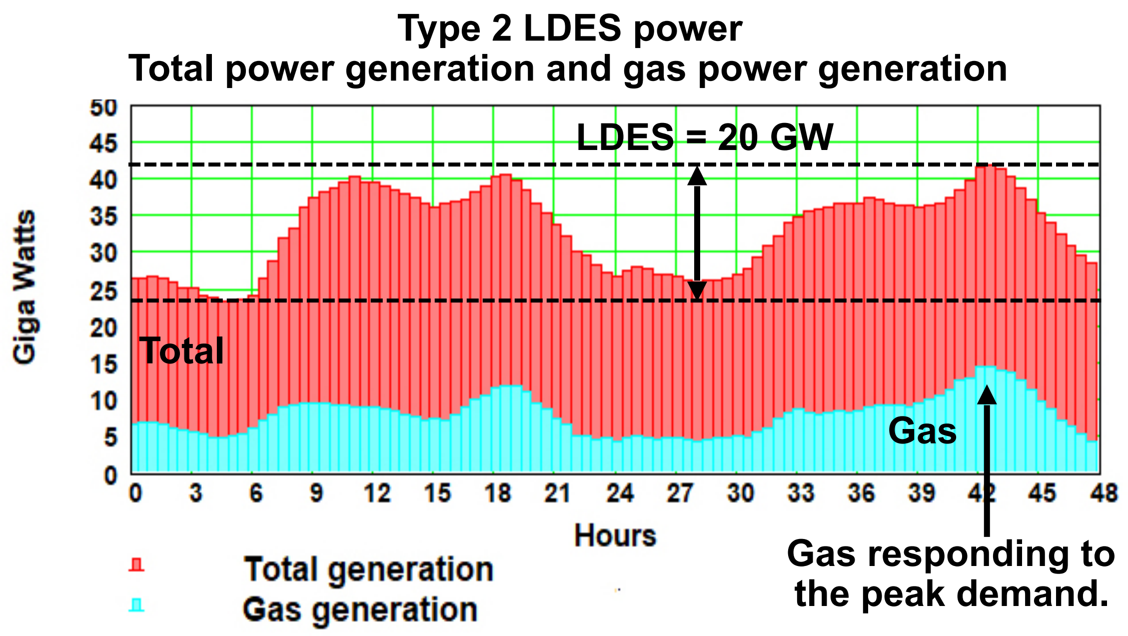
A **HVDC** system rated above the **MPT** value must be subdivided, including the **HVDC** cables, to avoid transients over the **MPT**.

Step 4. A reliable GB AC Grid



- This is an example of a **Local Zone** of the GB AC Grid that has reliable power generation.
- The Units are the same as **Step 3** and all important Units have now passed the proposed **Type Test.**
- Any power transient up to the **MPT** will not cause other Units to trip that avoids the risk of a cascading shutdown event.
- The system has adequate power reserves for at least two **MPTs**, and if needed can have a fast start of the **SCGT and CCGTs.**
- The next **Step** is to increase the **LDES** Units to fully control the daily power variations.
- The **FES23** states that 18 GW of inverter based energy storage systems are planned to be operational by 2028.
- Can now continue to add **LDES,** to add reliable renewable energy generators and to remove fossil fuel generators.

The three types of Energy Storage Units



Type 1. Short Duration Energy Storage:

- The **SDES** Units stabilise the GB AC Grid for a few seconds.

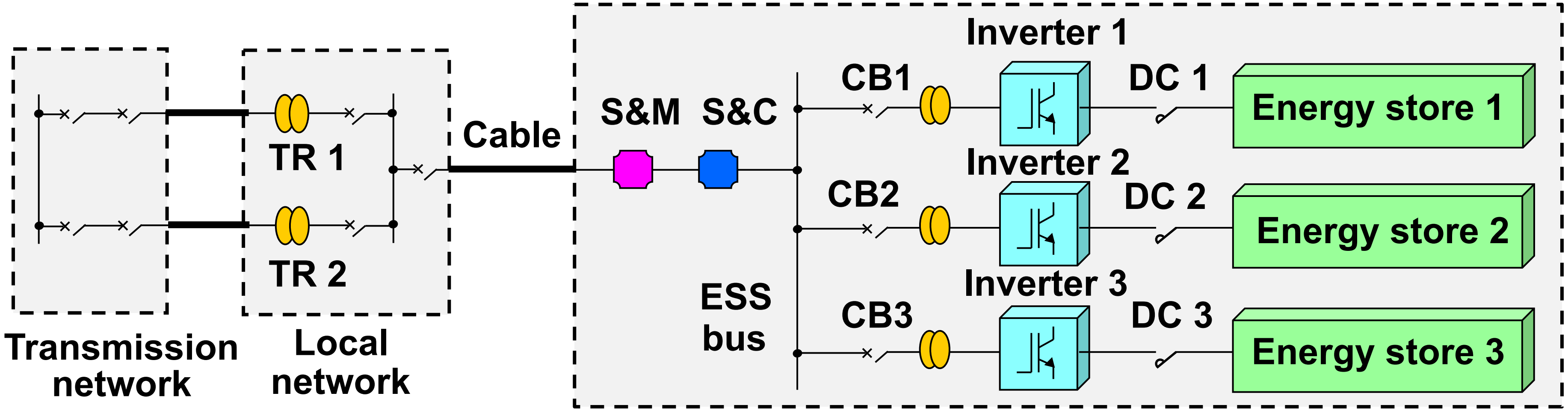
Type 2. Long Duration Energy Storage:

- The **HVDC** links shown on Slide 7 will help to stabilise the Gid's power flows in a time scales of 30 plus minutes.
- The **LDES** Units are used for controlling the GB AC Grid and provide extra power within a few seconds.
- The **LDES** Units can be engineered to use a very wide range of technologies including Flow Cell Units, Lithium Ion battery Units, Hydrogen storage Units and Thermal storage Units.
- This includes Units based on inverters and all types of primary power units using synchronous generators with a fast output power response.
- The rise time of the output power should be very fast, like one second, and the duration should be measured in hours.
- These should be capital assets purchased for a long in service life including through life costs.
- The 2024 Gov UK Long duration electricity storage consultation has a requirement for 20 GW, with a minimum rating of 100 MW per Unit and with a storage time longer than 6 hours.

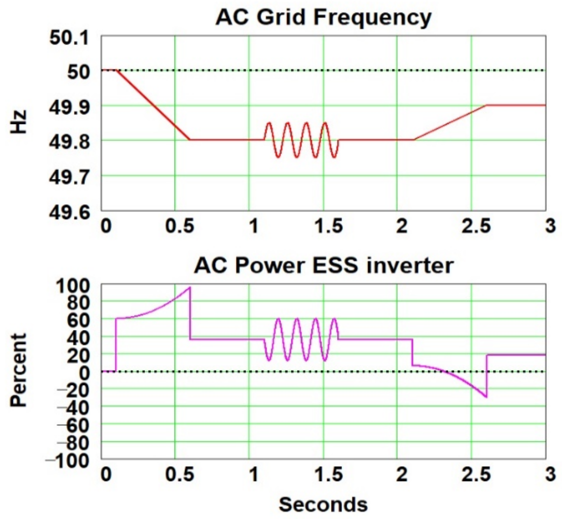
Type 3. Dunkelflaute Duration Energy Storage:

- The **DDES** Units supply power for a **Dunkelflaute** event.

The design of a LDES optimum ESS GBGF inverter



S & M = Sensors and Monitoring. S & C = Sensors and Control



- An **ESS GBGF** inverter uses many identical **GBGF** inverters in parallel to give a Unit with redundancy and high availability.
- The required energy can be stored in a range of different battery technologies including Lithium Ion batteries, Hybrid Ultra capacitor with integrated lead acid batteries and flow cell batteries.
- It is essential to use designs that are totally safe from a fire and a total meltdown, as a failure in a Lithium Ion battery can happen to one cell on a very rare basis due to an internal cell fault without any other system failure.
- The estimated failure rate is one cell per year in a 250 MW 125 MWh **ESS**. This has been validated in an IEEE webinar. The **ESS** design must allow for this fault without harming personnel and with minimal damage and safe designs are available.
- This Unit has the same 0.6 pu ratings, like the **Basic GBGF** inverter, for **Active Phase Jump Power** and **Active Inertia Power.**
- An **ESS GBGF** inverter responds to AC Grid's frequency errors versus the defined frequency and it can have **Droop Control.**
- An **ESS GBGF** inverter can also deliver a 1 pu of **Active Control Based Power** for a defined time duration but requires a higher **Peak Current Limit,** typically 2.1 pu**,** to simultaneously deliver all these abilities.
- The graph shows the response if a **Fast Frequency Droop Control** response is used to provide **Active Inertia Power.** This gives the wrong action for a **System Split** and the **System Split Inhibit Control** is used to correct this problem.

The use of the System Split Inhibit Control to correctly supply Active Inertia Power

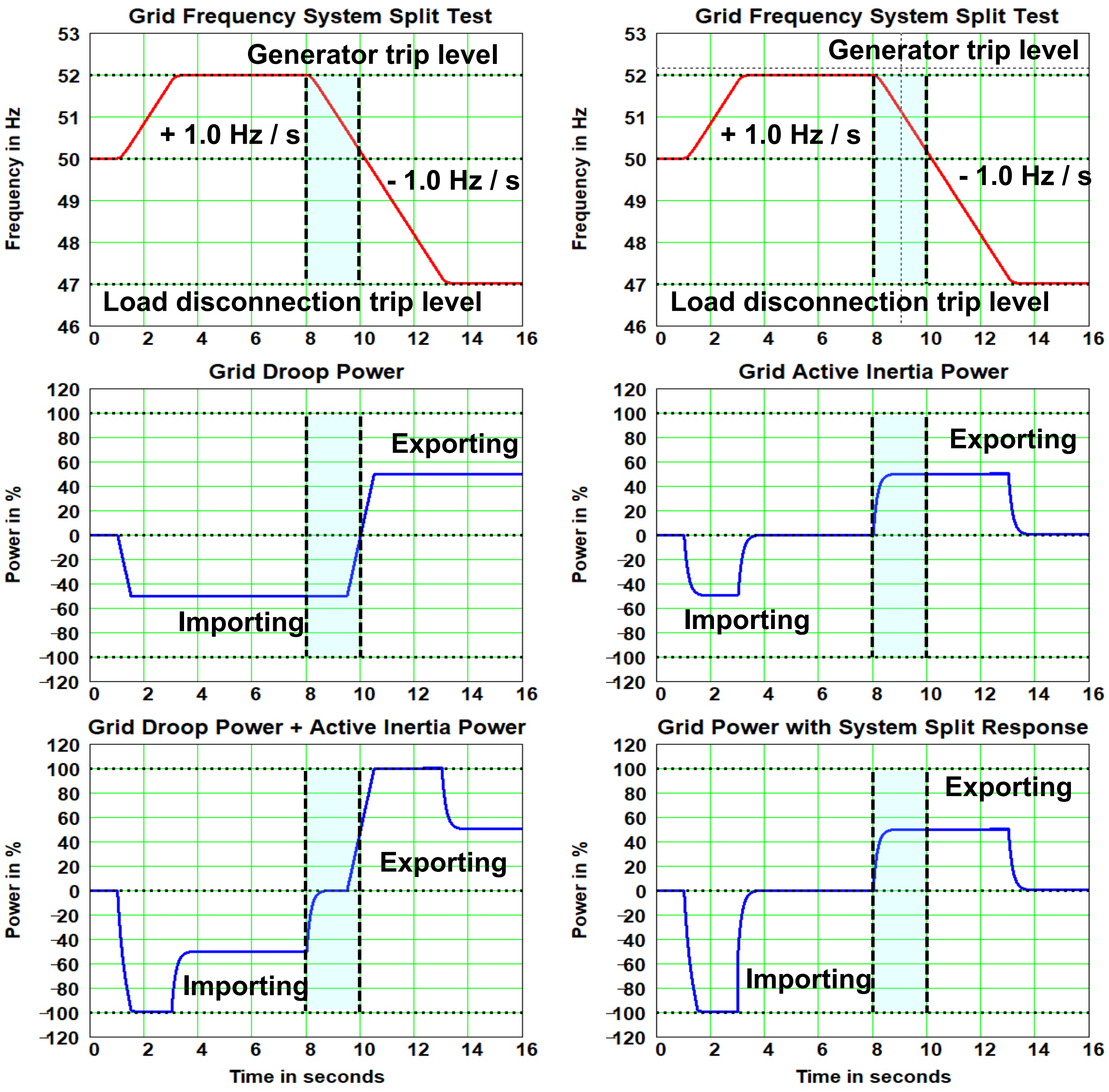
These three traces are for a **GBGF** inverter without the **System Split Inhibit Control.**

The critical time period is shaded in blue for the Grid frequency with a **RoCoF** rate of -1 Hz / s starting at a Grid frequency of 52 Hz.

The middle traces shows the Droop power for an **ESS GBGF** inverter with a 50 % **Droop Power** rating.

This has the incorrect polarity in the blue area and acts to increase the Grid's **RoCoF** rate.

The lower trace shows the resulting Grid **Power** for an **ESS GBGF** inverter without the **System Split Inhibit** Control with a 50 % **Active Inertia Power** rating that supplies zero Grid power.



These three traces are for a **GBGF** inverter with the **System Split Inhibit control.**

The critical time period is shaded in blue for the Grid frequency with a **RoCoF** rate of -1 Hz / s starting at a Grid frequency of 52 Hz.

The middle traces shows the **Active Inertia Power** for a **Basic GBGF** inverter that acts to limit the **RoCoF** rate.

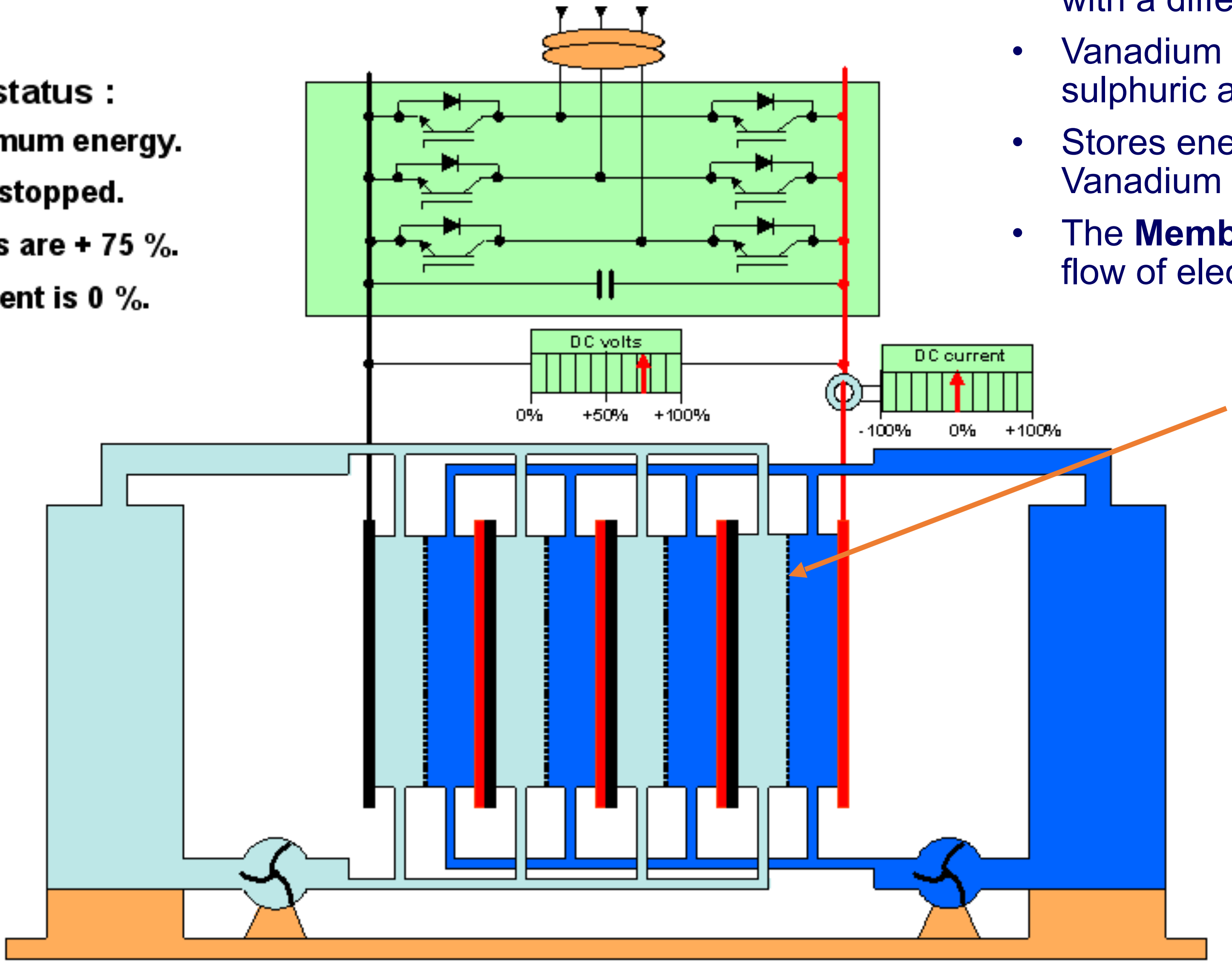
The lower trace shows the **Active Inertia Power** for an **ESS GBGF** inverter that has the **System Split Inhibit Control** which also acts to limit the **RoCoF** rate.

The **System Split Inhibit Control** stops the **Droop Power** if the frequency reaches either trip level and is cancelled when the frequency reaches 50 Hz.

The charging and discharging of a basic vanadium flow cell

System status :

- At minimum energy.
- Pumps stopped.
- DC volts are + 75 %.
- DC current is 0 %.



- Vanadium has four different oxidisation states each with a different voltage.
- Vanadium has low toxicity and is dissolved in dilute sulphuric acid.
- Stores energy in the fluid by adding electrons to the Vanadium molecule, with no loss of energy in storage.
- The **Membrane** allows the flow of protons to allow the flow of electrons from the PWM inverter.

Uses many **Unit Cells** in series to build a **Reaction Module** and each **Unit Cells** has two half cells separated by a **Membrane.**

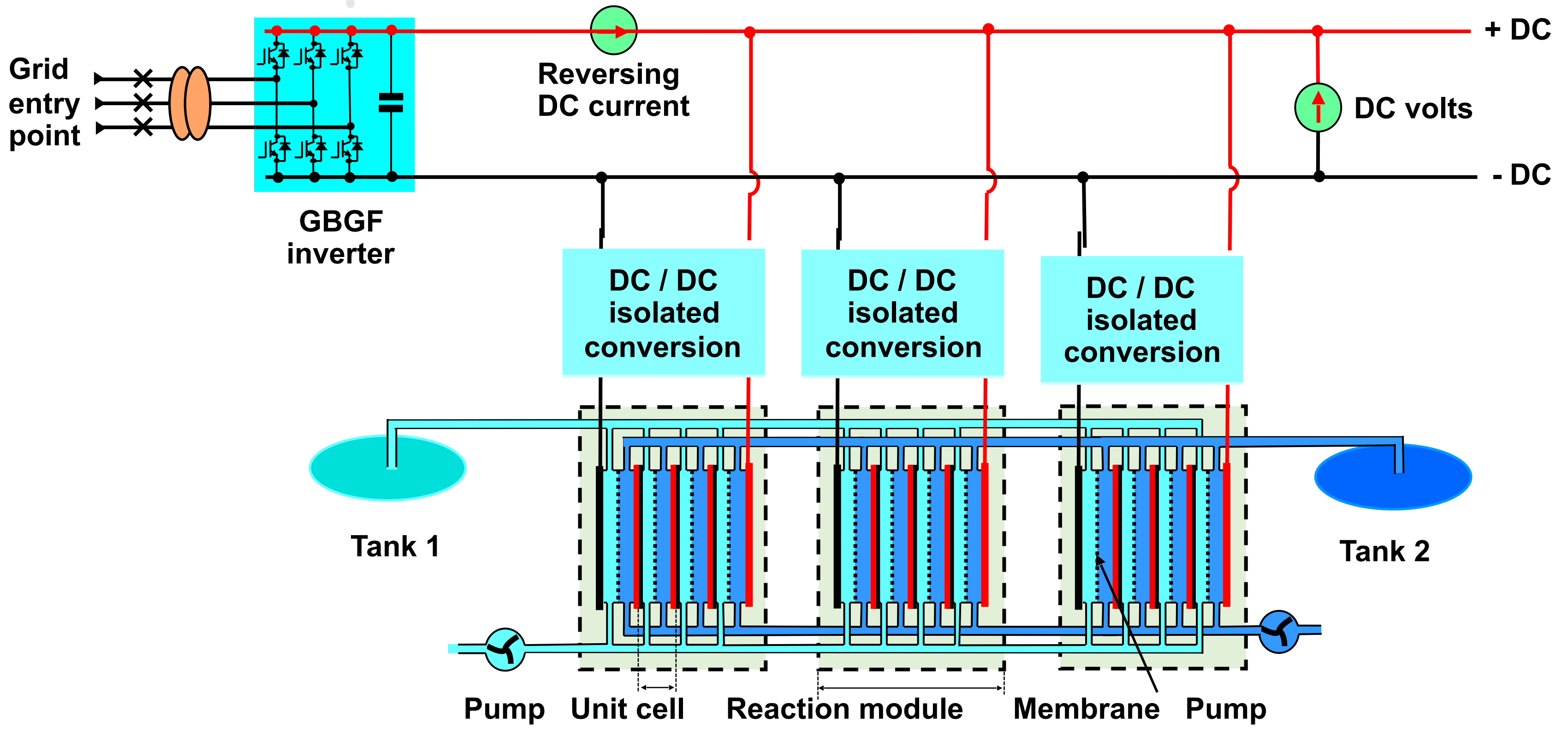
A good design is 30 **Unit Cells** in series to give a 50 volt DC **Reaction Module**.

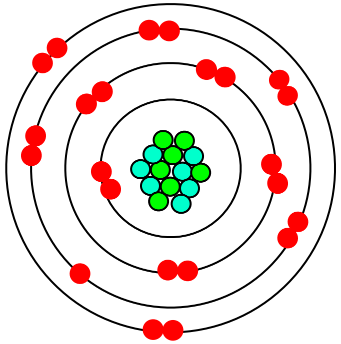
Extra **Unit Cells** in series causes losses due to currents circulating between the **Unit Cells** in the conductive fluid.

For lowest cost should use **COTS PWM** inverters as used for renewable energy systems with a DC voltage of 1000 to 1500 volts DC.

As the same fluid is used either side of the **Membrane** a pin hole does not damage the fluids which is not true for rival technologies

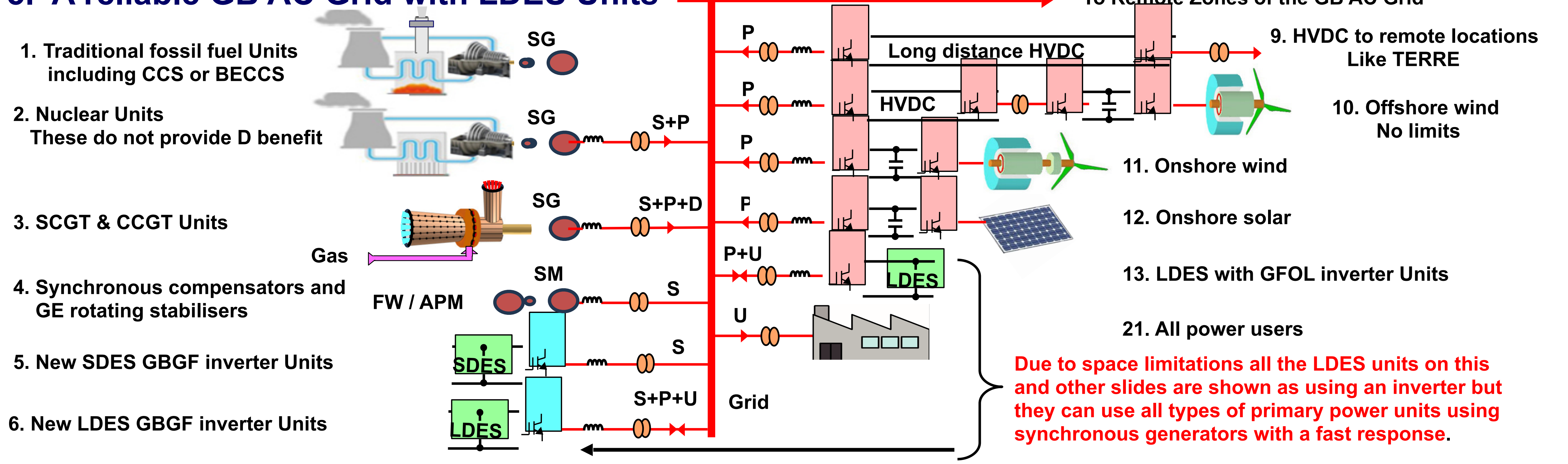
A proposed design for a Vanadium Flow Cell to provide SDES and LDES





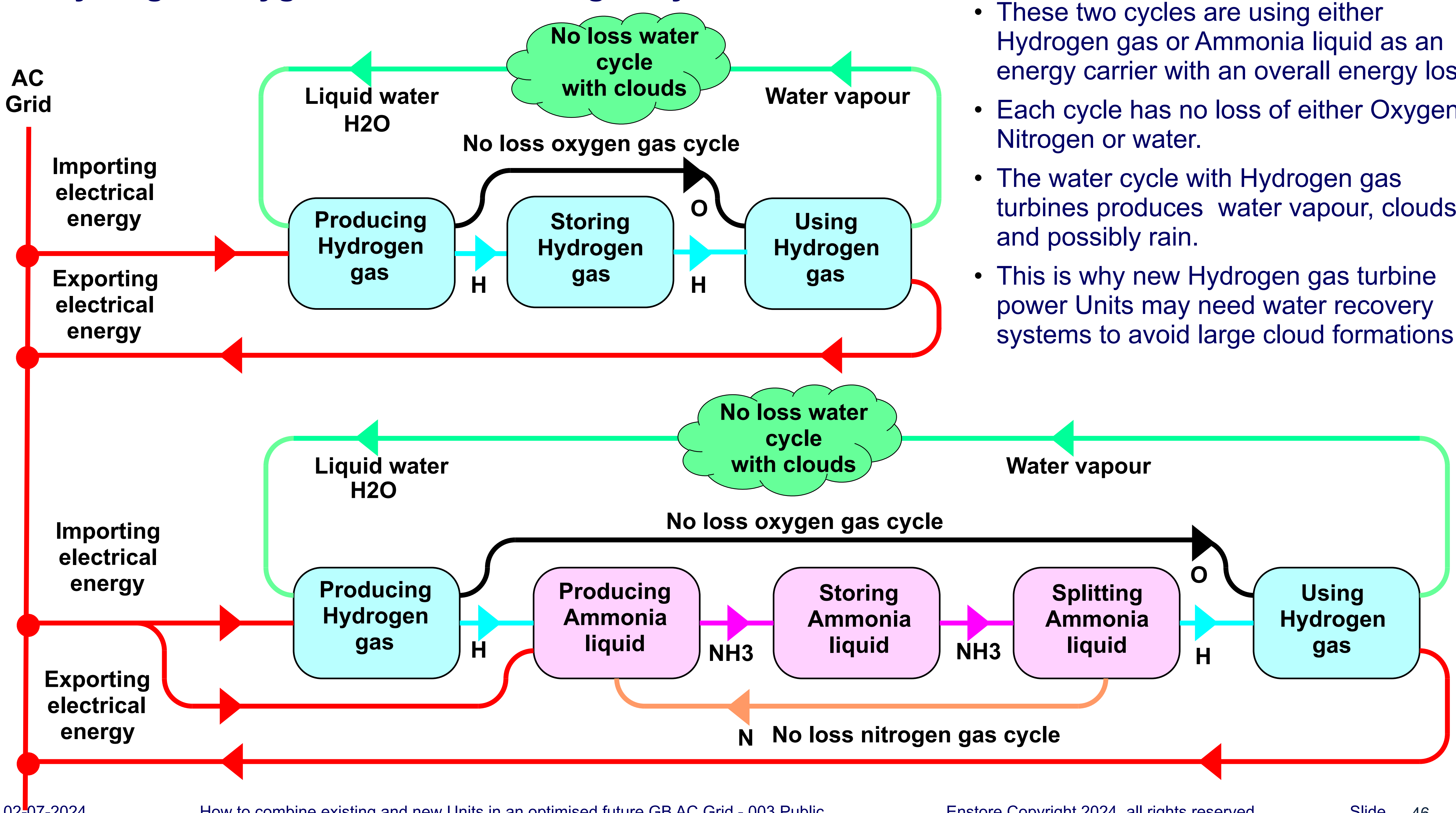
- Energy is stored by altering the number of electrons of each vanadium molecule dissolved in dilute sulphuric acid. The round trip efficiency is typically 75%, there is no loss of energy during storage and the storage fluid lasts indefinitely.
- These **ESS** are required to be available on a 24 / 7 basis and should be secured as a design with a long in service life time to minimise future capital costs and with the correct control the Unit has a very fast response of less than 20 ms for rated power.
- **Enstore** considers that the proven Vanadium redox flow cells are probably the optimum **ESS** design as the energy is stored directly by adding / subtracting electrons to the Vanadium molecules for an unlimited operating life.
- The circuit uses isolating DC / DC converters to enable two large storage tanks to be used together with the **Reaction Modules** operating at the optimum voltage level, and for a longer storage time than 6 hours, like 1 day, just add more fluid in larger tanks.
- With a GBGF inverter this system can provide all the GB services from one unit including **SDES** and **LDES.**

5. A reliable GB AC Grid with LDES Units



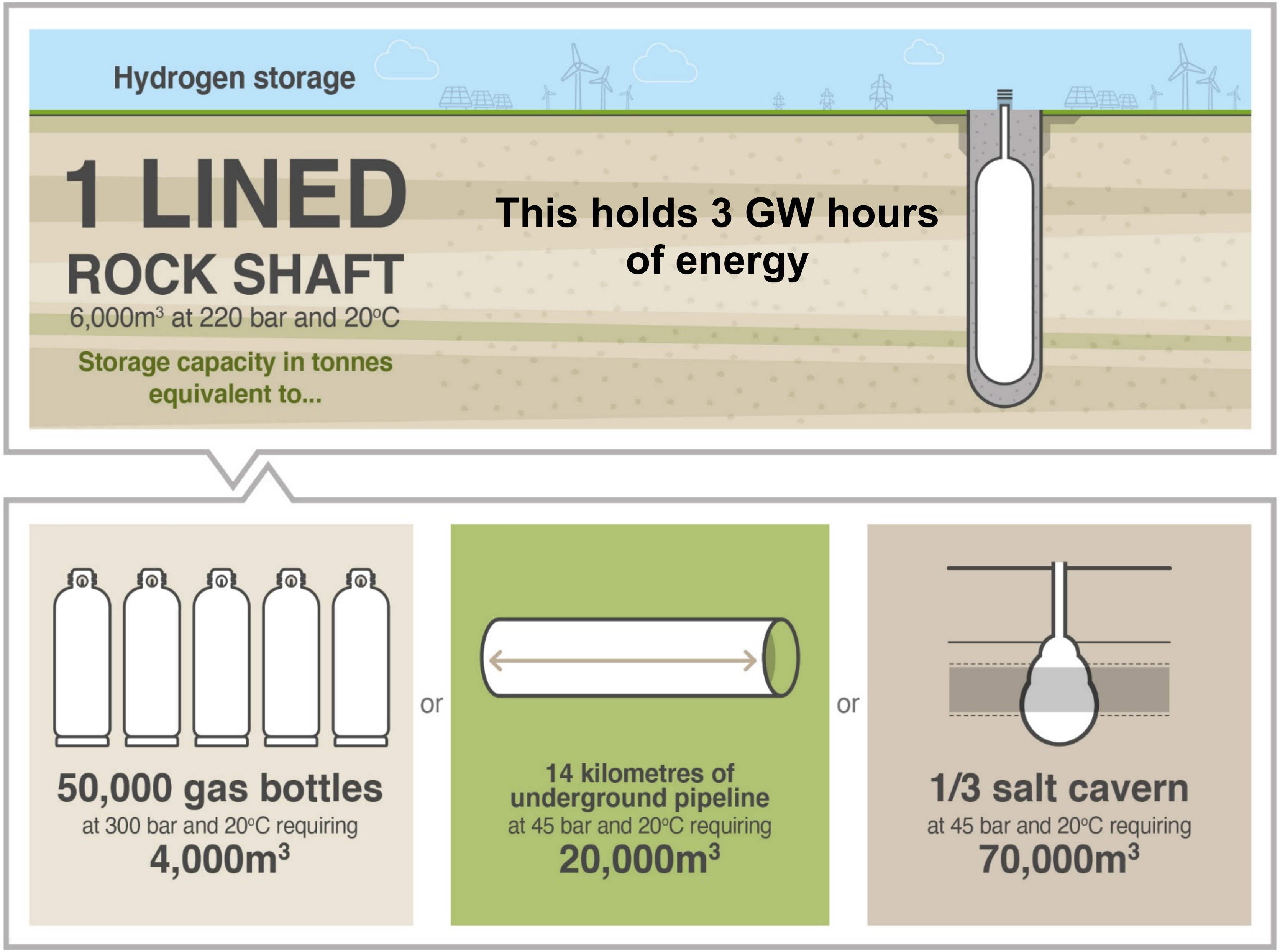
- This is an example of a **Local Zone** of the GB AC Grid that is fully stabilised and reliable with a significant value of **LDES.**
- Can now install and use the planned magnitude of renewable power systems without constraint payments.
- The **LDES** Units are able to control the variations between the required demand and the available power generation plus trips. This includes Units based on inverters and all types of primary power units using synchronous generators with a fast response.
- For the Unit 3 fossil fuel generators, the use of the **LDES** Units is likely to result in them being used on a very infrequent basis, however the existing and new fossil fuel Gas turbines are a way to supply power reserves including reserves for a **DDES** event.
- This may require operating these Units, on a regular basis to maintain their availability, even when their power is not required.
- In the same way the fossil fuel Unit 1, including Carbon Capture & Storage "**CCS**" and or Bioenergy with **CCS** "**BECCS**", are very likely to become unviable to operate on an intermittent basis. This is why they are shown as permanently disconnected.
- This GB AC Grid can now develop the Hydrogen power Units.

The Hydrogen, oxygen, water and nitrogen cycles



- These two cycles are using either Hydrogen gas or Ammonia liquid as an energy carrier with an overall energy loss.
- Each cycle has no loss of either Oxygen, Nitrogen or water.
- The water cycle with Hydrogen gas turbines produces water vapour, clouds and possibly rain.
- This is why new Hydrogen gas turbine power Units may need water recovery systems to avoid large cloud formations.

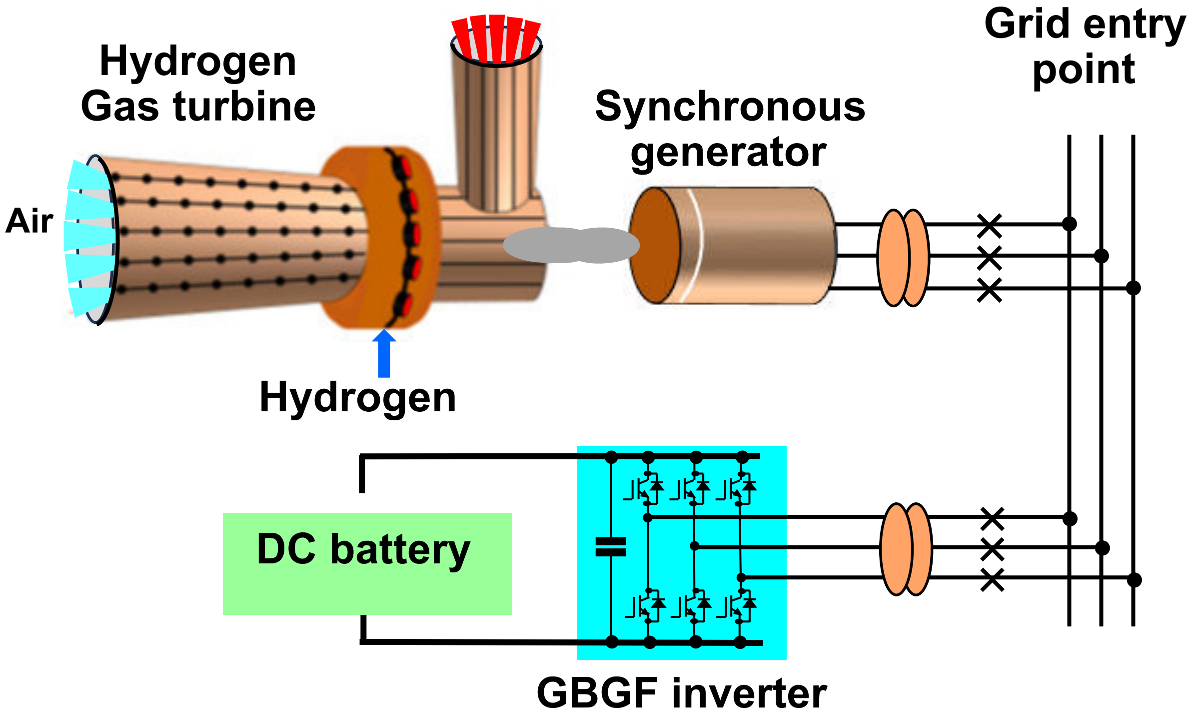
The proposed Hydrogen storage technology that is being developed.



Storage data:

- Pressure 220bar.
- Temperature at 20 ^{0}C.
- Density 15 kg / m cube.
- Tank 6000 m cube.
- Holds 90,000 kg.
- Hydrogen is 120 MJ / kg.
- Tank holds 10.8 GJ.
- This is 3 GW hours.
- 3 tanks are equivalent to a large salt cavern and can be located where needed.
- This avoids the need for an expensive Hydrogen distribution network with a number of Hydrogen compressor stations.
- In **Enstore's** opinion this is the optimum Hydrogen storage method.

Future Hydrogen synchronous generator Units



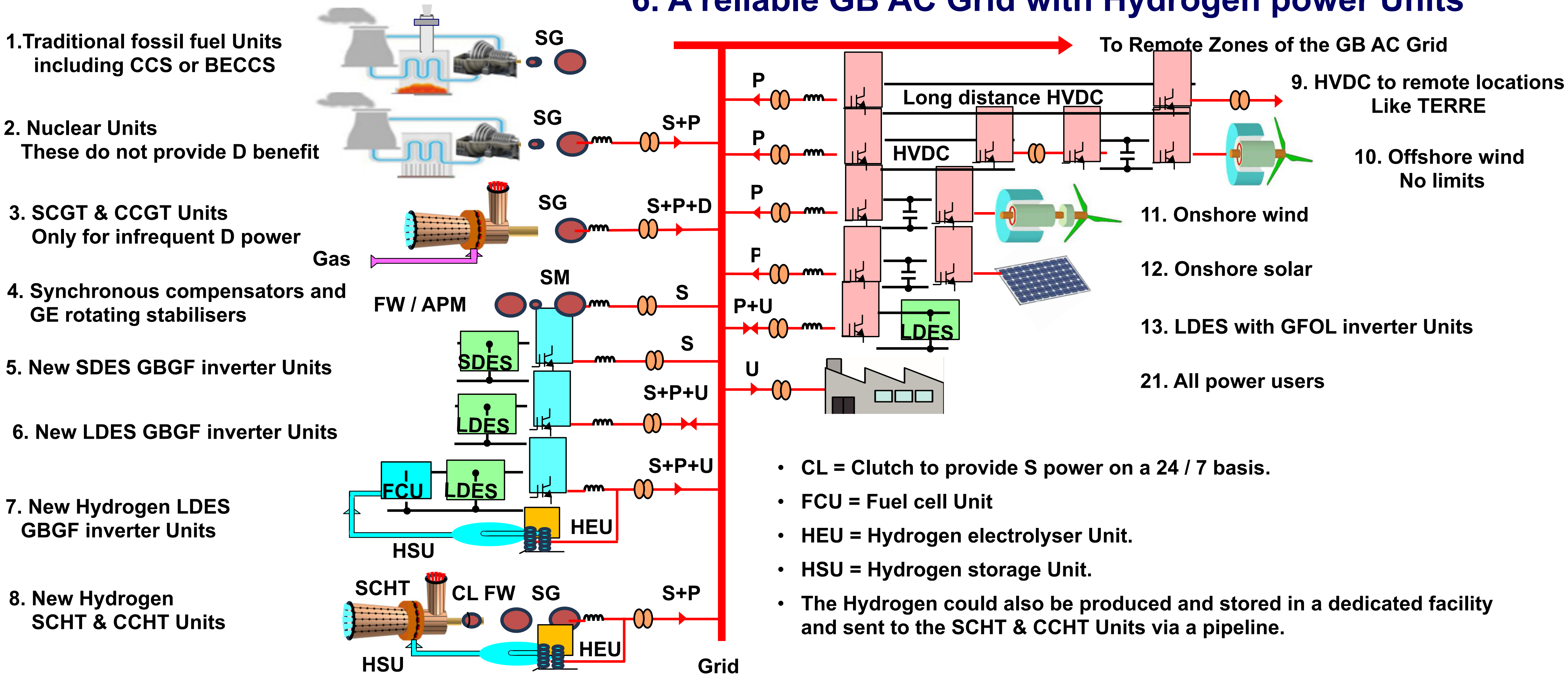
Can add a parallel GBGF inverter to add extra benefits:

- Can increase the power ramp rates from the combined system.
- Can run the turbine at a constant load for maximum efficiency.
- Can minimise CO2 emission and increase system efficiency.
- Can provide on demand extra power with a 1 second response.
- Can provide primary and secondary response power.
- Can provide an increased level of **Active Inertia Power.**

Operation of the Synchronous generator:

- The availability of **LDES** Units with a significant rating will compensate for the daily power variations and will also rapidly supply extra power if one or more **MPT** trips occur.
- As a result any new Hydrogen gas turbine Units may only operate on a very infrequent basis during time periods with low levels of renewable power.
- This will probably require a new type of contract, with **NGESO,** to maintain a high availability for these Units by operating them on a weekly basis, for several hours, even when their output power is not needed.
- This operating method is the exact opposite of constraint payments that could result in constraint payments to other renewable power generating Units.
- This type of power Unit needs a **NGESO** pilot project ASAP to validate the technology.
- The ideal location is the sites of fossil fuel Units.
- A more detailed design is shown on a later slide.

6. A reliable GB AC Grid with Hydrogen power Units

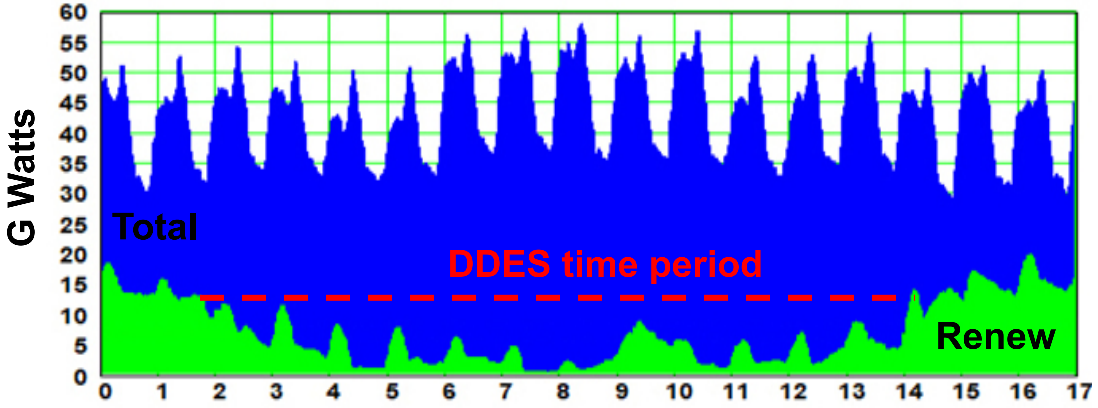


- CL = Clutch to provide S power on a 24 / 7 basis.
- FCU = Fuel cell Unit
- HEU = Hydrogen electrolyser Unit.
- HSU = Hydrogen storage Unit.
- The Hydrogen could also be produced and stored in a dedicated facility and sent to the SCHT & CCHT Units via a pipeline.

- This is an example of a **Local Zone** of the GB AC Grid that is fully stabilised & reliable with a significant value of Hydrogen **LDES** that includes Units based on inverters and all types of primary power units using synchronous generators with a fast response.
- All the **LDES** Units give very good control of the GB AC Grid's power flows and the synchronous generators Units 3 and 8 will only be needed on a very infrequent basis. This will need special operating rules to make them viable to own and to allow sufficient weekly running to keep them reliable, even if their power is not needed.

The requirement for DDES Units

Type 3 DDES power
Total power generation and renewable power generation



Days from the NGESO's power records in early January 2021

Type 3. Dunkelflaute Duration Energy Storage:

- The **DDES** Units supply power for a **Dunkelflaute** event that occurs when weather conditions produce a very low level of renewable power.
- These conditions can simultaneously affect large areas of the **EU** and a source of extra power is needed to avoid large scale power cuts in the GB AC Grid and the estimated storage is more than 100 GW days for the existing GB AC Grid.
- For future GB AC Grid with an increased level of renewable energy the **DDES** may need to provide up to 800 GW days.
- This power can be most economically provided by adding interfaces to either the Inverter based **LDES** and or the new Hydrogen turbine synchronous generators.

The required energy for a **Dunkelflaute** weather event:

- Needs to be available with very little notice.
- May need to be stored for several years until required, so needs an **ESS** with low storage losses.
- Is needed to keep the existing generators providing their rated power for this event, like the coal piles held for fossil fuel generators, as the **DDES** power is unlikely to be provided by the **HVDC** links as the **EU** has the same problems at the same time.
- **Will probably require a strategic reserve defined by a GOV UK mandate with GOV UK funding**.

Options for storing GW days of energy

Typical large Ammonia storage tank reproduced by permission of Fisher Tank. Com.

https://fishertank.com/2015/01/27/raise-the-roof-a-giant-ammonia-tank-takes-shape-in-nd/

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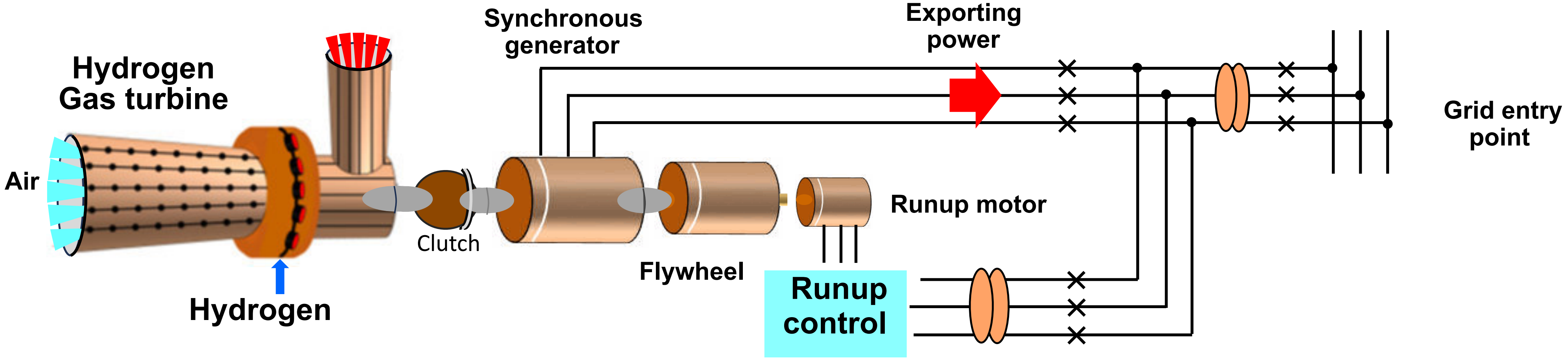
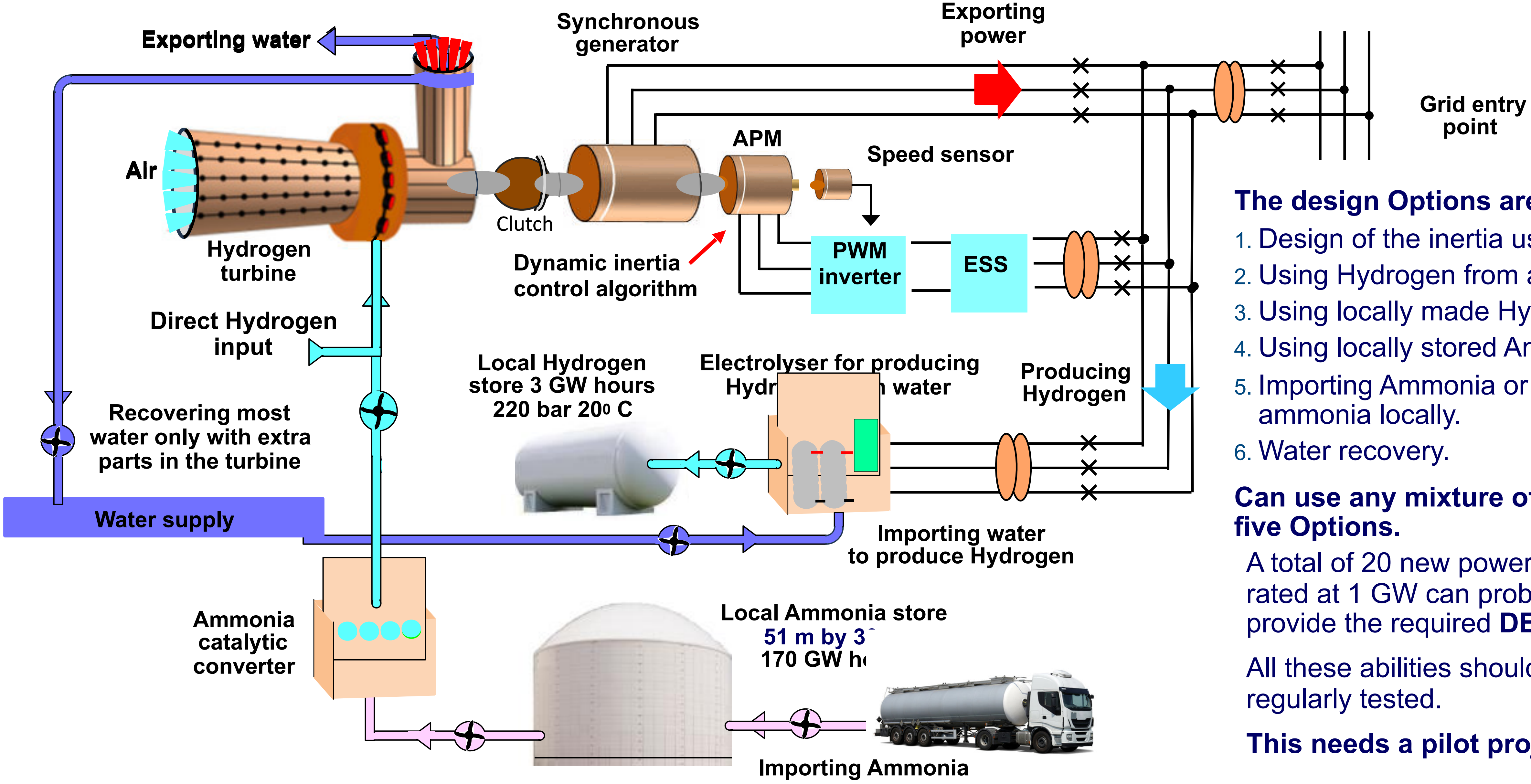
- For a **Dunkelflaute** weather event the stored energy must be available on short notice, that is independent of the daily storage systems, and must be available even if a **Dunkelflaute** weather event has not happened for several years.
- These requirements could cause possible problems with Hydrogen storage in salt caverns due to the typical Hydrogen cavern leakage loss rate of 1 % / day and possible long term Hydrogen contamination problems.
- The number of GB salt caverns are limited, the Mitsubishi data on their largest salt cavern is 150 GWh = 6.25 GW days, this is the basis of the **Enstore's** estimate that 16 salt caverns will be needed plus a Hydrogen transport Grid.
- Using Ammonia **NH_3** has an energy density of 12.7 MJ / L and has no carbon emissions and is a viable alternative.
- The large Ammonia tank, shown above, stores 30,00 ton of API 620 anhydrous Ammonia in a fully proven commercial storage tank that is 51 m in diameter and 30m high.
- The Ammonia is stored as a liquid at -33 degree C to be at atmospheric pressure with a typical loss of 0.04 % / day.
- The tank is located in North Dakota and contains an energy of 7 GW days at an estimated cost of approximately 132 £ / MWh and 30 tanks could provide 30 GW and 210 GW days.
- The world Ammonia production already exceeds 180 million metric tons (t) per year via over 120 worldwide ports.

Building a possible future Hydrogen turbine Unit



The options for building a possible future Hydrogen turbine power Unit



The design Options are:

1. Design of the inertia used.
2. Using Hydrogen from a Grid.
3. Using locally made Hydrogen.
4. Using locally stored Ammonia.
5. Importing Ammonia or making ammonia locally.
6. Water recovery.

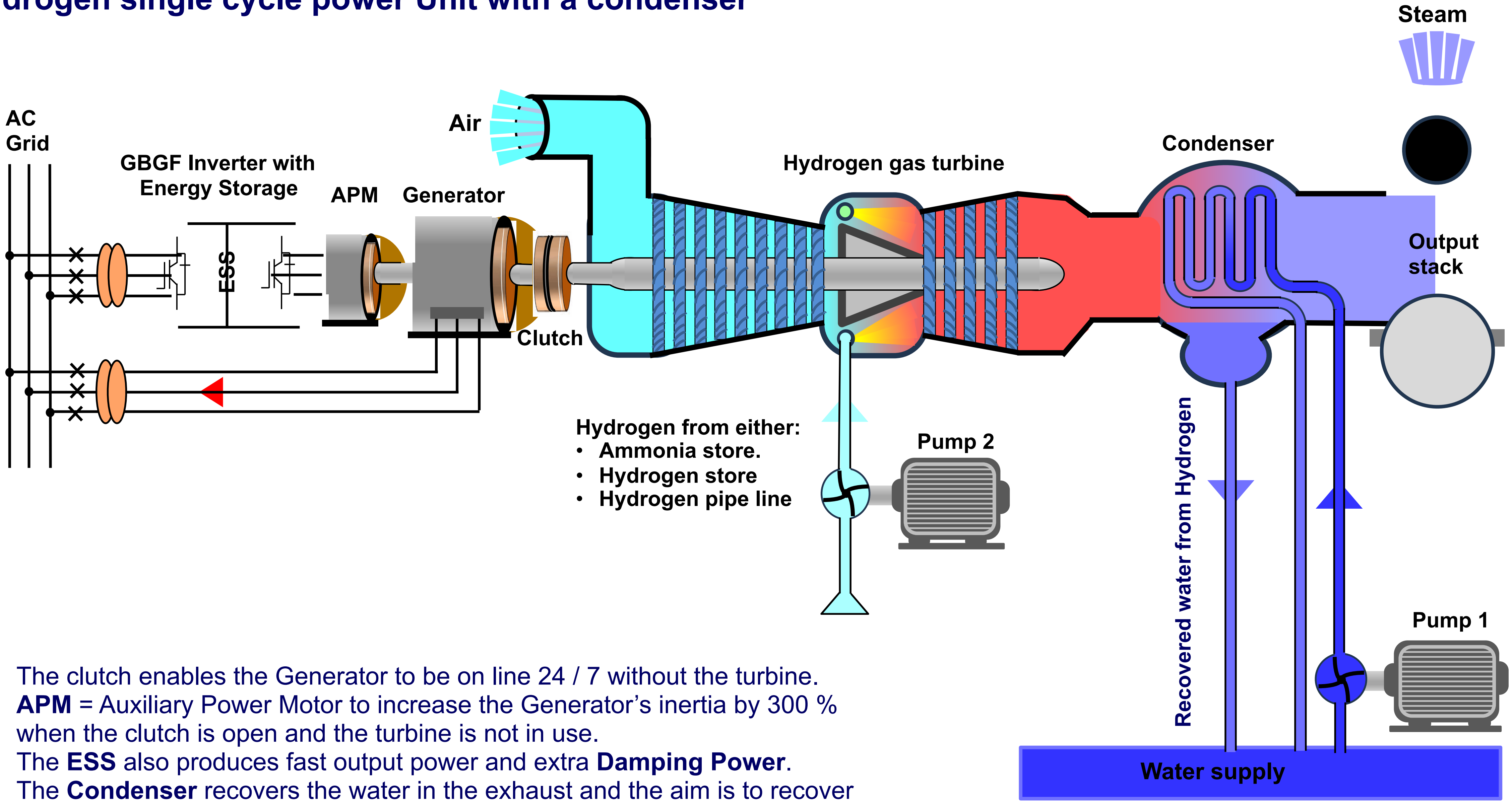
Can use any mixture of the five Options.

A total of 20 new power Units rated at 1 GW can probably provide the required **DESS.**

All these abilities should be regularly tested.

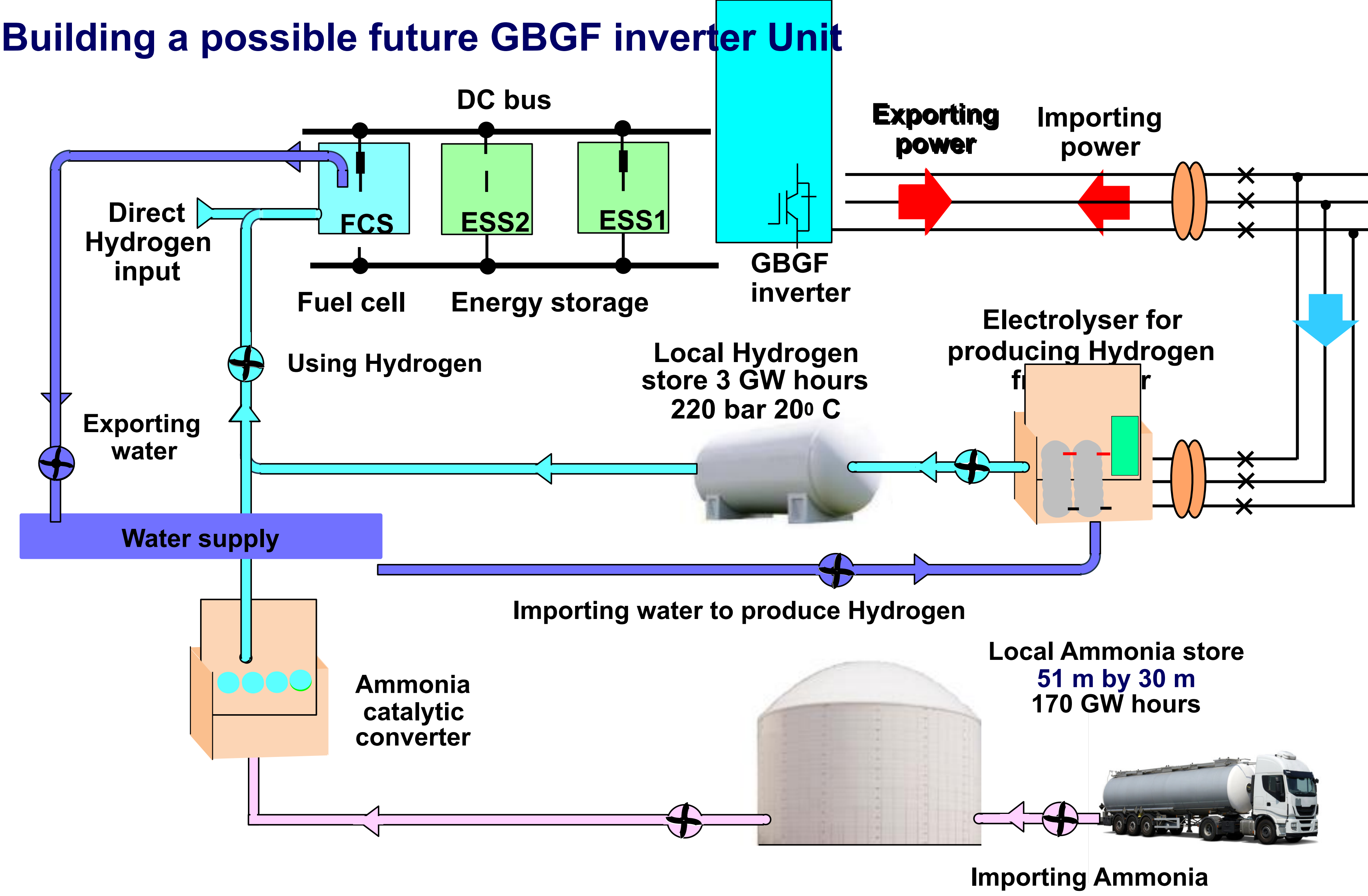
This needs a pilot project.

Hydrogen single cycle power Unit with a condenser



- The clutch enables the Generator to be on line 24 / 7 without the turbine.
- **APM** = Auxiliary Power Motor to increase the Generator's inertia by 300 % when the clutch is open and the turbine is not in use.
- The **ESS** also produces fast output power and extra **Damping Power**.
- The **Condenser** recovers the water in the exhaust and the aim is to recover most of the water used to produce the Hydrogen.

Building a possible future GBGF inverter Unit



The design Options are:

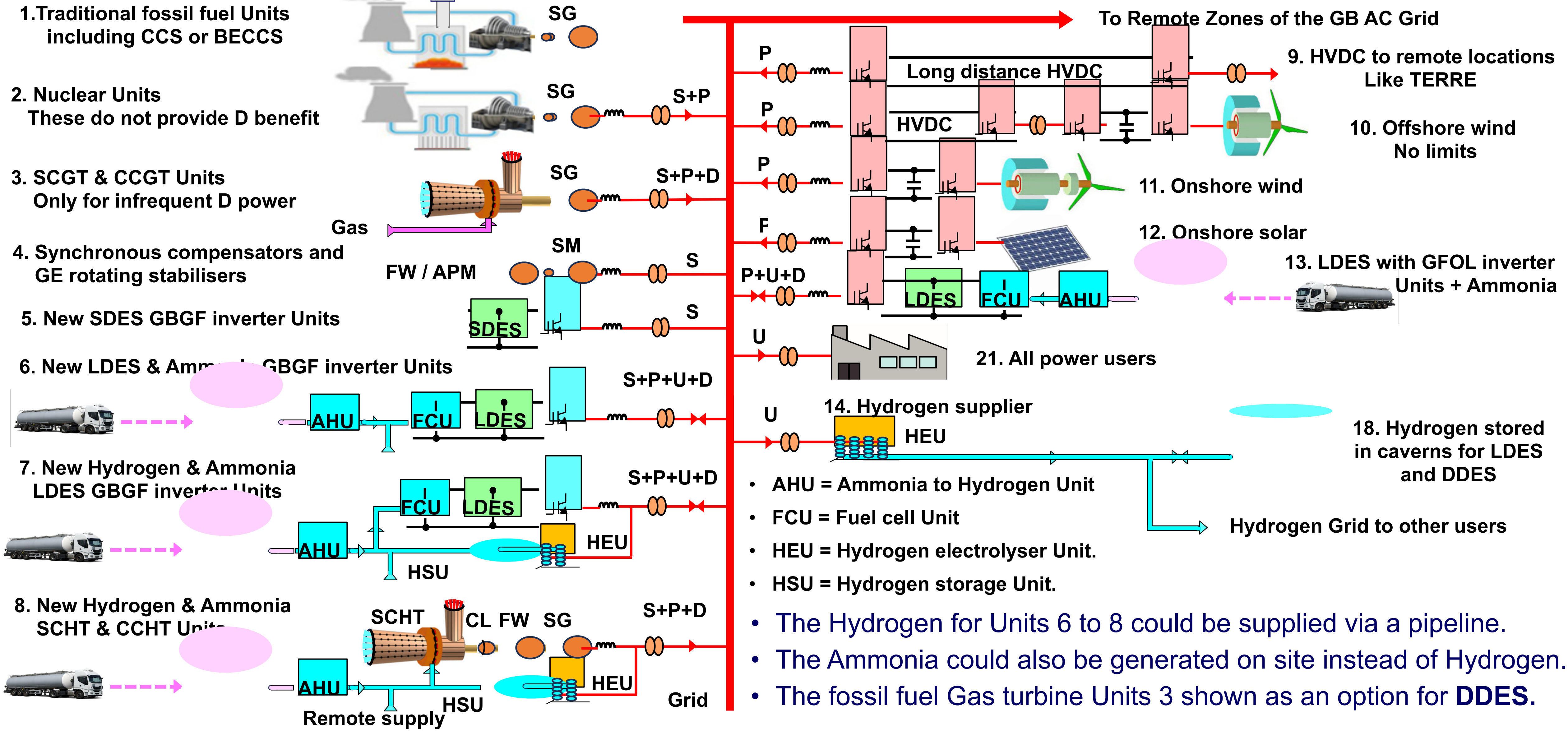
1. Using Hydrogen from a Grid.
2. Using locally made Hydrogen.
3. Using locally stored Ammonia.
4. Importing Ammonia or making ammonia locally.

Can use any mixture of the five Options.

This design is a viable alternative to synchronous generation and provides Grid stability for all conditions

This needs a pilot project.

7. A reliable GB AC Grid with DDES Units



- AHU = Ammonia to Hydrogen Unit
- FCU = Fuel cell Unit
- HEU = Hydrogen electrolyser Unit.
- HSU = Hydrogen storage Unit.

- The Hydrogen for Units 6 to 8 could be supplied via a pipeline.
- The Ammonia could also be generated on site instead of Hydrogen.
- The fossil fuel Gas turbine Units 3 shown as an option for **DDES.**

- The **LDES** Units are based on inverters and all types of primary power units using synchronous generators with a fast response that are in daily use and seem to be the lowest way to add **DDES**, as they do not need special payments like the **SCHT** & **CCHT** Unit 8 and the fossil fuel **SCGT & CCGT** Unit 3, but all options can be used.

Summary

There are four important challenges that must be solved which are:

- To maximise the efficient use of renewable energy.
- To replace fossil fuels power Units with of either inverter based and or Hydrogen based and or Ammonia based power Units.
- To have a GB AC Grid that is stable for a set of well-defined operational conditions.

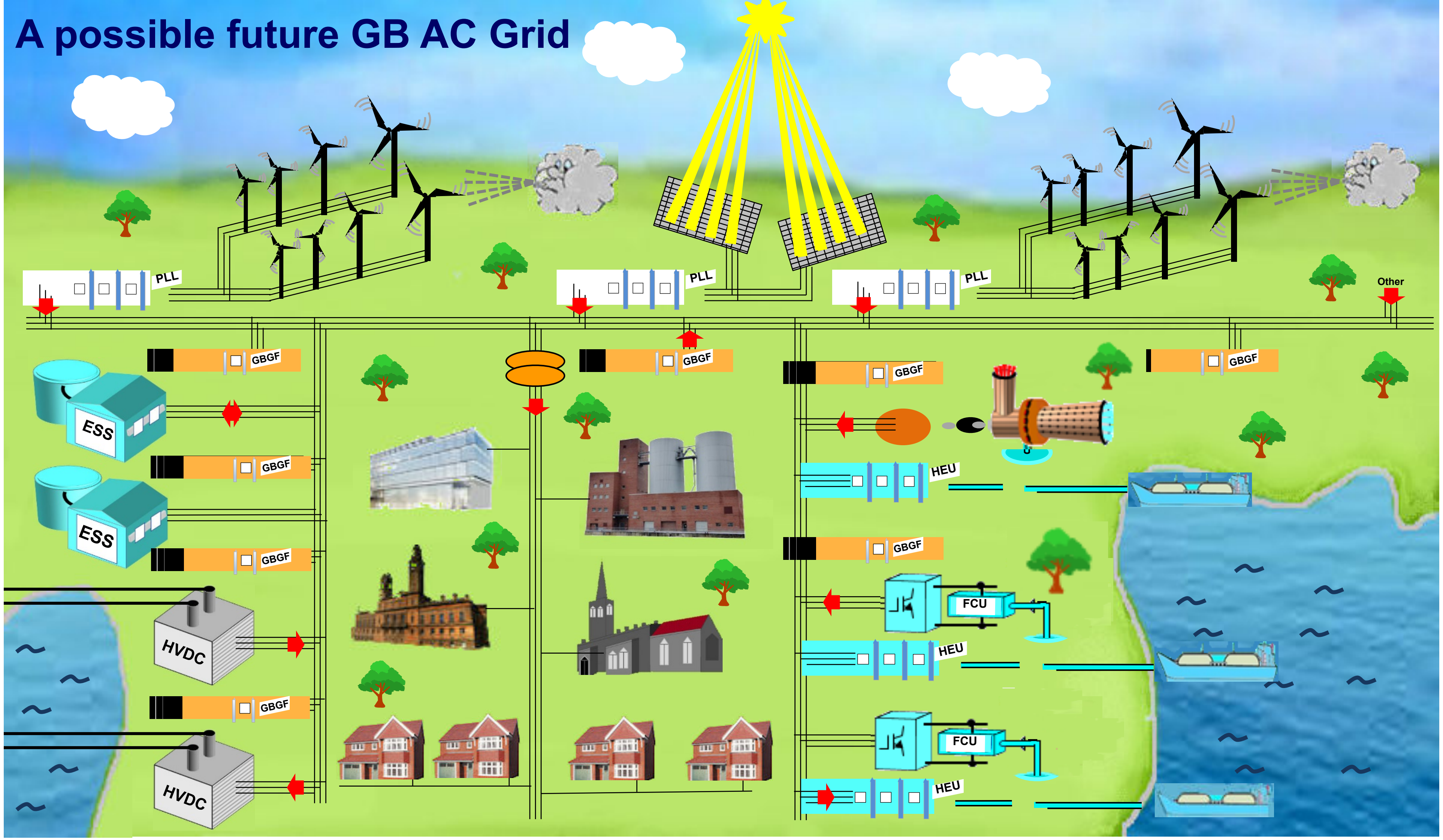
These challenges require the following:

- That the **Basic GBGF** and **ESS GBGF** inverters are available from suppliers.
- That the allowed **Maximum Power Transient "MPT"** is defined for both polarities, and may need to rise to 2 GW for **EGL1**.
- That the **Allowed Phase Jump Angle** is fully defined as well as a minimum defined Grid **Damping Factor**.
- The use of the **ETIV** concept for predicting a **Phase Jump Angle.**
- The deployment of Energy Storage Systems as capital assets with a long in service life.
- To hold viable power reserves for **Dunkelflaute** weather event.
- The development of new power Units based on either Hydrogen and or Ammonia.
- To have a market for **Active Phase Jump & Damping Power** so that **GBGF** inverters can compete with synchronous machines.

Summary:

- To have a **Stable GB AC Grid** each **Local zone** requires the installation of correctly rated **GBGF** generators and or **GBGF** compensators and or **GBGF** inverters.
- Future land based renewable energy systems can use either existing **PLL** or **GBGF** designs.
- Future offshore wind farms can use the existing proven designs.
- **HVDC** links can use either existing **PLL** based designs or **GBGF** based designs.
- For future power generating Units any Gas turbine Units or Hydrogen Turbine Units are only likely to be required on a very intermittent basis, however the **LDES** Units will be used 24 / 7 / 365 which is why they appear to be the best way to add a **DDES** ability based on stored liquid Ammonia and why they should be ordered with this as a future Option.

A possible future GB AC Grid



- The GB AC Grid is stable for a **Phase Jump Angle** transient on a **Local zone** basis.
- The GB AC Grid is running on renewable power with two **ESS GBGF** Units available.
- Extra power can be supplied by the **HVDC** links but it may only be available for a short time.
- For extra GB AC Grid power the Hydrogen / Ammonia based generators are started.

Thank you

Commercial conditions:

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