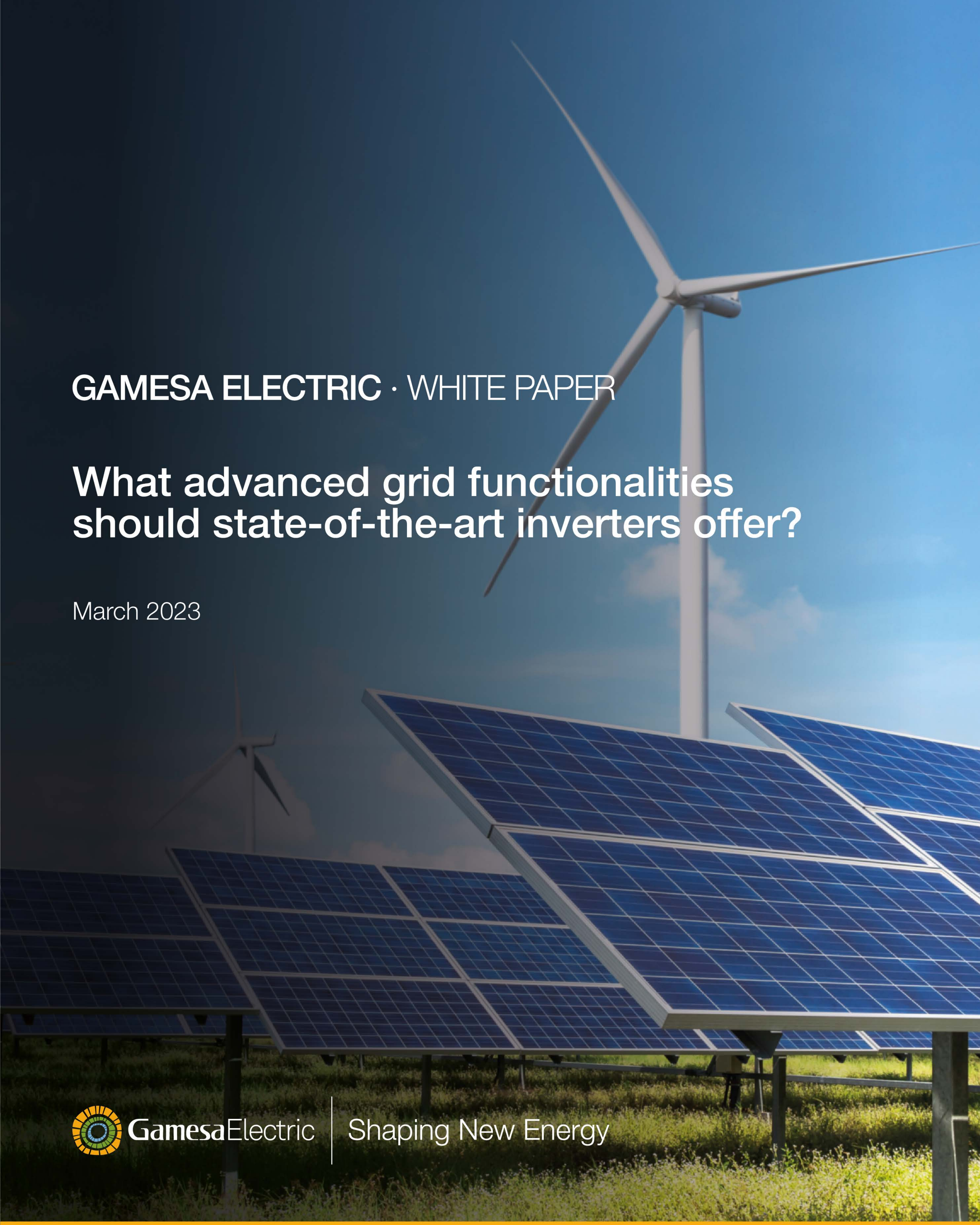
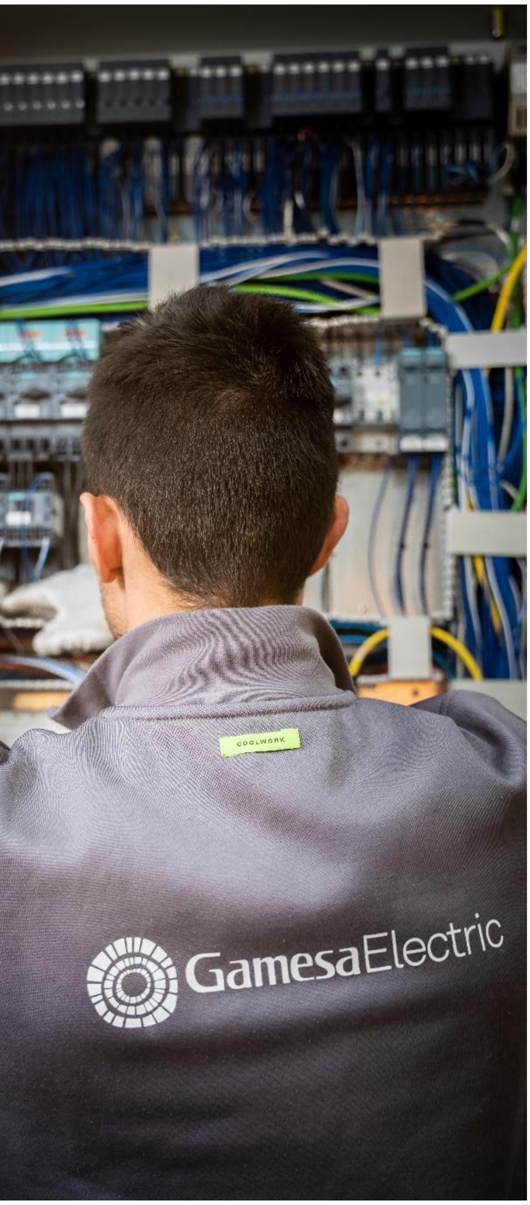
GAMESA ELECTRIC · WHITE PAPER

What advanced grid functionalities should state-of-the-art inverters offer?

March 2023



GamesaElectric | Shaping New Energy



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EXECUTIVE SUMMARY

The power generation industry is undergoing a dramatic change as renewable sources, distributed generation, decarbonization and demand increases are transforming traditional sources of energy. The reduced inertia present in the grid, due to the decommissioning of large power plants and the intermittency of renewables, poses significant challenges to its stability. As a result, frequency variations caused by momentary imbalances are higher and more recurring.

In this context, PV and battery storage inverters must fill the gap left by synchronous generators and be able to offer the same services in order to ensure stable and secure grid operation. So-called *grid-forming* inverters are the new generation of equipment that incorporate the necessary functionalities to be active elements in grid operation.

These grid functionalities include among others Fast Frequency Response or Black-Start.

The Gamesa Electric Proteus family of state-of-the-art inverters together with the Gamesa Electric Orchestra controller (plant controller) are a clear example of equipment designed to be able to meet the most demanding grid requirements. This document describes the main functionalities incorporated in the most advanced inverters together with the results of real tests to which the Proteus equipment has been subjected in order to test its capabilities.

BACKGROUND

01

In a world where the energy is playing a more important role and the decarbonization of the energy sources is becoming a higher priority of governments with zero carbon operation as final target, renewable sources are paramount to achieve these goals. However, the transition to cleaner energies is not a direct step, existing several obstacles to overcome.

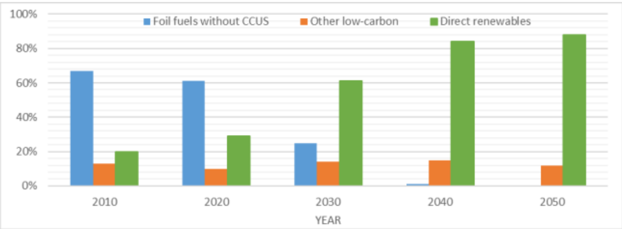


Figure 1. Expected integration of renewable sources. Source: IEA

Traditional grid generators are based on large rotating machines; devices that transform the mechanical energy into electrical energy. Hydroelectric, nuclear and coal-fired power plants share the same basic concept; they take in advantage certain type of energy to drive a rotating machine that generates electrical power. In this environment, large generators are all connected to the distribution grid where utilities and grid operators (TSO – Transmission System Operator) act as orchestra conductors managing the power grid components. The generation units are part of a team where the lack of one is supplied by others; if an individual generator cannot reach the requested setpoint (due to fuel capacity limitation or water flow saturation, for instance), the TSO will adjust the setpoints of other generators in order to compensate the shortfall and ensure the operation.

Within the available technology of traditional generators, the most widely used device is the synchronous generator, an electrical machine whose shaft speed has a direct relationship with the frequency of the grid. This allows it to adjust its voltage output and respond to changes in grid frequency by modifying its operating point. These devices greatly contribute to the power grid stability due to the damping they provide against disturbances.

In a general view

The stability of any power grid is achieved by controlling the following parameters:

- ✓ Voltage control. The adjustment is performed by controlling the reactive power through devices such as synchronous generators (which allow the dynamic control), capacitor banks or inductive loads.

- ✓ Frequency control. The balance between the power generated and the power consumed ensures a steady grid frequency, variations of any value will cause a frequency change that has to be corrected by modifying the active power (by modifying the mechanical speed in the case of synchronous generators).[1]

- ✓ Rotor angle control. It's related with rotor angle stability, the capacity of a synchronous generator to keep synchronism after a disturbance, i.e. the ability to maintain the equilibrium between both mechanical and electromagnetic torques. The disturbance may accelerate or decelerate the rotor speed, so the different speed respect to generators of the same grid affect to its angular position and may lead to instability.

Figure 2. 4x12.1 MVA hydro generators manufactured by Gamesa Electric

[1] See Annex 4 for further details

However, the grid stability is being affected by the aforementioned decarbonization process: which consists of replacing of traditional large generators by renewable energy sources (solar, wind and energy storage) based on power-lowered decentralized units composed of electronically controlled devices (power converters). The progressive substitution of large generators is becoming an increasing challenge for TSOs, which must ensure the grid reliability and stability despite of the entry of these new players while maintaining a null impact on end-users. As a result, TSOs are forced to impose new features and functionalities on these new energy sources to ensure proper grid operability, coining new terms such as *smart grid, grid-forming* or *black-start*.

In this context, Gamesa Electric has a wide product portfolio for photovoltaic and energy storage applications that meet the most demanding requirements. The Proteus family of power converters offers the best product performance in utility-scale applications and includes all the new advanced functionalities highly demanded by system operators

GRID SUPPORT WITH RENEWABLE SOURCES

02

The addition of new energy sources based on power electronic converters to replace rotating electrical machines is leading to variations in the grid behavior during frequency control regulations. Power electronic converters have a completely different behavior in comparison with rotating machines; on the one hand they have a very short timescale response, and on the other, they don't contribute to system damping created after a frequency change due to absence of massive rotating shafts. This decrease in inertia capacity affects the grid control and, in the worst case, it could destabilize it. To address this, grid operators are imposing grid support capabilities to ensure the grid stability.

From the grid point of view, a power converter is able to work in 2 operation modes according to how it interacts with the grid; *grid-feeding* (traditional on-grid) mode and *grid-forming* mode where the converter has the ability to create the grid whenever it is necessary. In these modes, the equipment is able to provide several functionalities (also called ancillary services) necessary for grid support.

Grid-feeding (current source)

In grid-feeding mode (also known as grid-following), the power converter behaves as a current source and the grid sets the voltage, being the inverter control system synchronized with said voltage. Functionalities like frequency or voltage regulation are achieved by controlling the exported active and reactive power.

In BESS (Battery Energy Storage Systems), the converter control calculates the current reference and hence the modulation signals based on requirements of active and reactive power (sent by power plant controller) and the battery status (sent by BMS – Battery Management System); charge level (SOC) and battery health (SOH).

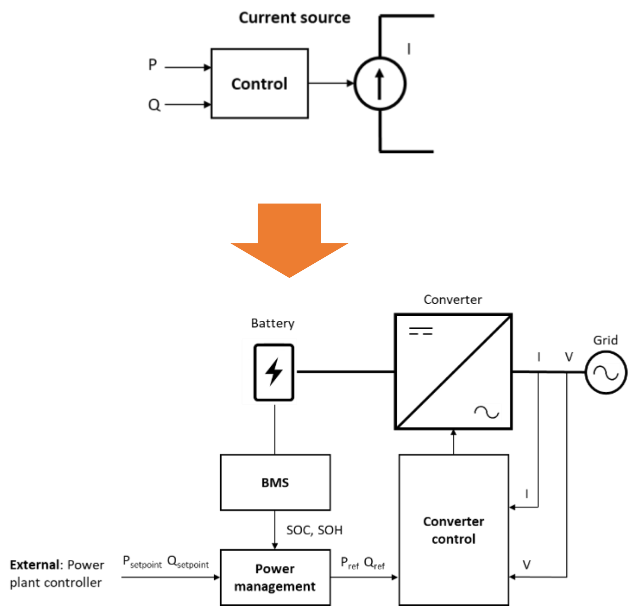


Figure 3. Basic scheme of grid-feeding BESS converter

Nevertheless, the large-scale penetration of renewable energy sources is leading to a significant decrease in the grid inertia capacity, making the grid more sensitive to abrupt changes in power. In this framework, the grid-forming mode goes further than grid-feeding mode and allows emulating the behavior of a synchronous machine.

Grid-forming (voltage source)

In grid-forming mode, the converter is a voltage source (it can create the electrical grid by itself) with the ability to modify its operation according to external setpoints. Therefore, all functionalities available in grid-feeding mode are also available here. The control strategy used is known as Virtual Synchronous Machine (VSM) where the inverter control is capable of emulating the synchronous generator behavior.

The PCS receives 2 groups of set points; on the one hand, the necessary parameters for grid voltage creation (voltage magnitude —Vac—, frequency —f— and phase angle —θ—) and, on the other hand, the power references (active power —P— and reactive power —Q—) according to grid demands (in a similar way to a grid-feeding converter). Besides, as it will be explained later, the system has the possibility of emulating the behavior of a synchronous machine because is capable of providing the necessary support in case of voltage outage.

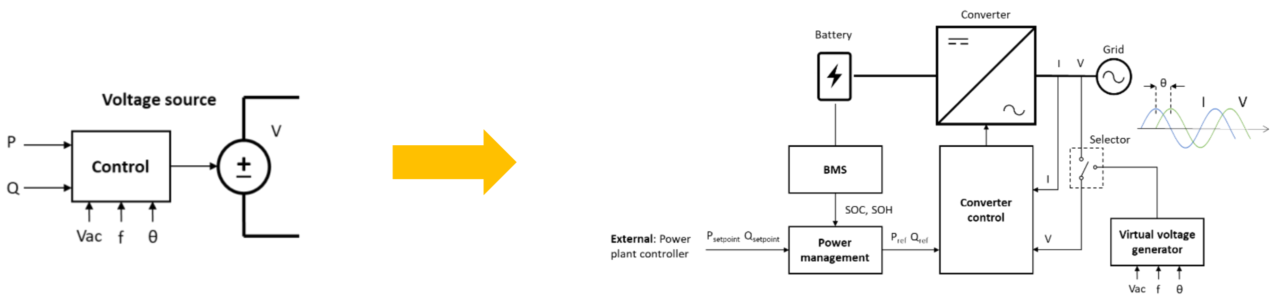


Figure 4. Basic scheme of grid-forming BESS converter

The next table summarizes which functionalities (explained with further details in the following sections) **are available in each operation mode.**

Functionality	Grid-feeding inverter	Grid-forming Offgrid	Grid-forming Ongrid[2]
Voltage regulation	✓	✓	✓
Power factor control	✓	X	✓
Active and reactive power ramp rate	✓	X	✓
External setpoints (secondary frequency control, energy shifting, trading…)	✓	X	✓
SI (Synthetic Inertia)[3]	✓	✓	✓
PFR (Primary Frequency Response)[4]	✓	✓	✓
FRT (Fault Ride-Through)	✓	✓	✓
POD (Power Oscillation Damping)	✓	X	✓
Islanding operation	X	✓	✓
Black-start	X	✓	X
VSM (Virtual Synchronous Machine)	X	✓	✓

[2] See Annex 3 for further details
[3] Part of FFR (Fast Frequency Response)
[4] Part of FFR (Fast Frequency Response)

STANDARD FUNCTIONALITIES 03

The next table shows the ancillary services included by default in Proteus PCS.

Voltage regulation

The PCS generate reactive power in order to control the AC voltage at desired value. This control can be performed in 2 different points:

- ✓ At PCS terminals (LV side), thus the PCS has a Q-V curve (defined by grid code) which is internally programmed in the firmware (predefined in the parameter set).

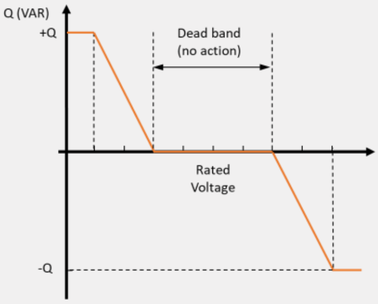


Figure 5. Generic Q-V curve

- ✓ At power plant POI, the calculation of the necessary reactive power is made by power plant controller (Orchestra) and is received by PCS via setpoint.

Power factor regulation

In the same way as with voltage regulation, it´s possible to regulate either the power factor or reactive power at the power converter terminals or at the Point Of Interconnection (POI). This can be carried out with two methods:

- ✓ Power factor vs. Active power droop (PF-P droop): this curve is usually defined by grid code. It receives the measured active power as input and generates a power factor setpoint as output, which is then transformed into a reactive power setpoint.

- ✓ Power factor control: the power factor setpoint received by communications is directly transformed into a reactive power setpoint.

Active and reactive power ramp rate

The PCS can modify the active and reactive power according a predefined maximum ramp (defined by the grid code), i.e. a limitation of how quickly the active and reactive power can change.

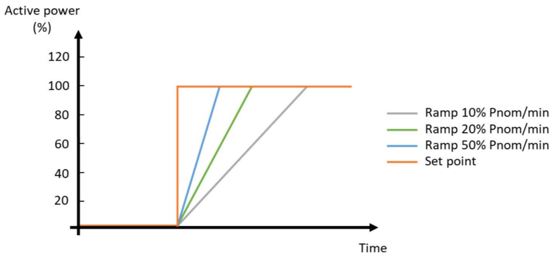


Figure 6. Examples of ramp rates for set points from 0% to 100% of rated power

Fast Frequency Response (FFR)

This is the most basic functionality required to ensure grid stability. The grid codes define the system response by means of curves in which the active power changes as a function of the frequency value. The response must be fast enough, which is why they are normally requested at the inverter level in order to avoid communication delays. However, one of the main advantages of the Gamesa Electric Orchestra controller is that its fast response time allows it to perform the FFR functionality rather than at the inverter level.

The Fast Frequency Response can be divided into 2 stages:

- *Synthetic inertia (SI).* It's the stage that can most quickly support the grid, which is gaining special relevance due to progressive replacement of synchronous generators, as stated in the previous sections. These generators limit the system unbalance in the event of a sudden frequency change due to its inherent mechanical inertia. Therefore, the synthetic inertia algorithm (also called virtual inertia) aims to emulate the behavior of these generators by responding to the rate of change of frequency (ROCOF) through a variation of active power. System operators set the maximum allowable ROCOF, above which the converter must be shut down.

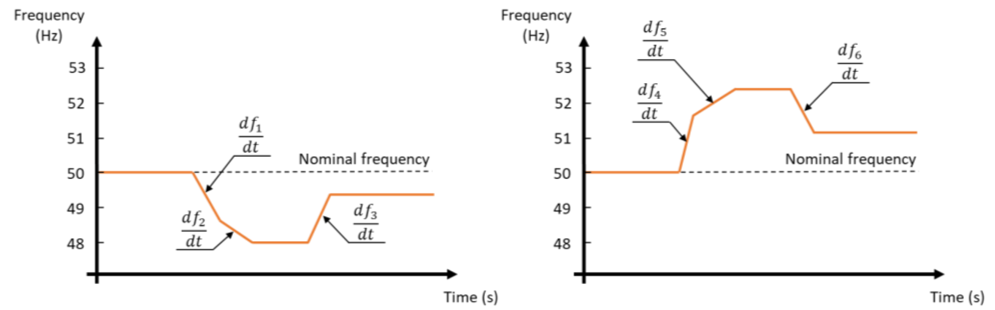


Figure 7. Profiles of ROCOF limits for over-frequency and under-frequency events

- *Primary Frequency Response (PFR) or frequency droop.* The PCS reaction can be activated autonomously based on the converter frequency measurement or it can react according to an external setpoint sent by the plant controller. The reaction is defined by a P-f droop curve. In addition, grid codes also limit the time the system can operate in over-frequency and under-frequency conditions: if after a certain time the nominal frequency is not restored, the system must be shut down. The P-f droop curve can be configured for different points and different slope levels (see next figure), which allows a perfect adaptation to any requirement.

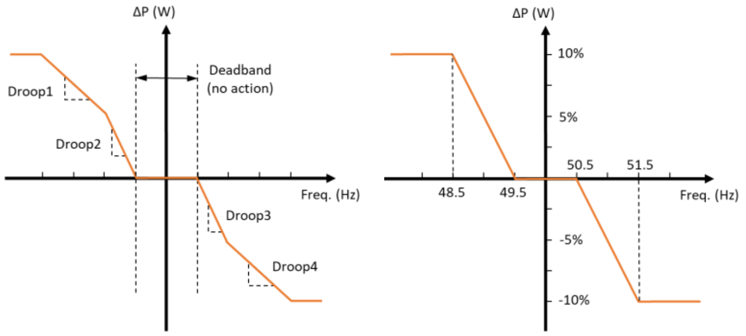


Figure 8. P-f droop curve features (left). Example of grid code requirement (right)

Fault Ride Through (FRT) – VRT (Voltage Ride Through)

This feature is related to the ability of power converters to remain connected in the event of voltage disturbances. Grid codes define voltage-time profiles that any grid-tied equipment must withstand. Two scenarios can be distinguished:

- ✓ HVRT (High Voltage Ride Through) is the equipment capability to remain connected during a transient voltage swell in the grid, therefore disconnection is not allowed below the voltage-time profile defined by the grid code. Above this curve, the equipment is not required to remain connected.

- ✓ LVRT (Low Voltage Ride Through) is the equipment capability to remain connected during a transient voltage dip in the grid. As in the previous case, the disconnection limit is delimited by the voltage-time profile.

Gamesa Electric Proteus PV and PCS are able to withstand voltage dips down to 0% of rated voltage for 1 second.

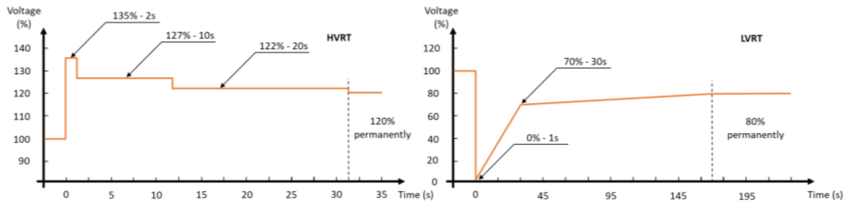


Figure 9. Maximum HVRT and LVRT profiles of Proteus PCS and PV

Power Oscillation Damping (POD)

Other problems that disturb the grid stability are the low frequency inter-area power oscillations due to the presence of long transmission lines between loads and large generators. The effect is more pronounced the more power is transmitted and the weaker the connection. Furthermore, the integration of inverter-based renewable sources adds sudden power variations and reduces the system inertia and short-circuit levels, which also contributes to increasing these oscillations. The result is the occurrence of low-frequency oscillations in the power across the line with a typical frequency range between 0.1 Hz and 2.5 Hz, with a potentially negative effect on grid stability.

In traditional power grids, the oscillation mitigation (damping control) is managed by rotor angle stability, i.e. the ability of synchronous machines to maintain the mechanical and electromagnetic torques after being disturbed. They include voltage regulators in the generator excitation system that modify the rotor electrical torque and dampen any oscillatory effects.

In the case of power converters, oscillations are mitigated through closed-loop control strategies that adjust the output power according to the grid variations. This control affects both active and reactive power and is performed at the plant controller level. The control performance can be adjusted according to the conditions of each installation. according to conditions of each installation.

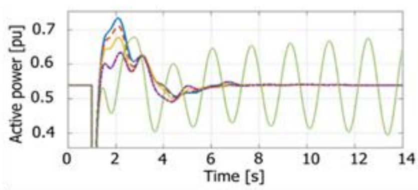


Figure 10. Simulation results of POD control using different adjustment parameters

ADVANCED FUNCTIONALITIES 04

The present document considers as advanced functionalities the different variants of grid-forming mode, which in turn has 2 depending on its operation; Offgrid mode (also called islanding operation) and Ongrid mode (also called parallel operation).

OFFGRID MODE – ISLANDING OPERATION

The present mode requires the PCS can start after a blackout, what means that the ability to start without power grid supply is mandatory, i.e. the *black-start* option is necessary.

Description

The equipment generates the voltage grid based on input parameters of voltage amplitude, frequency and phase. Active and reactive power are determined by load demand and the supply is ensured whenever the maximum converter capacity is not exceeded, in which case the system will shut down. For another hand, once the grid voltage is restored, the system has the ability to synchronize the generated voltage with the mains to avoid any short-circuit during the reconnection thanks to phase-shifting setpoint adjustment carried out by the plant controller (Orchestra).

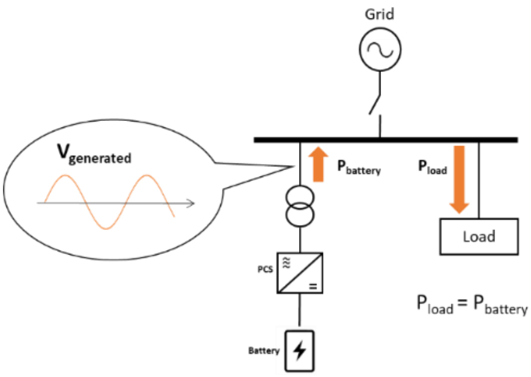


Figure 9. Example of converter working in Offgrid mode (islanding operation)

Simulation

How Gamesa Electric Proteus and Orchestra can handle a contingency in an islanded grid[5]

The test consists of demonstrating the stability of an islanded grid governed by BESS working as grid forming when all the synchronous generation trips.

The sequence is as follows:

1. The gas turbine is providing the total power demand of the loads (30 MW) while Proteus PCSs work in grid forming mode (parallel operation) without injecting active power.
2. The gas turbine trips (total loss of power generation).
3. The Proteus PCS set regulates voltage and frequency, restoring the power supply.

The next graphs show the system response after the contingency:

- ✓ Power evolution. After gas turbine power dropping (red line) the load power (green line) is quickly restored by Proteus PCS (blue line).

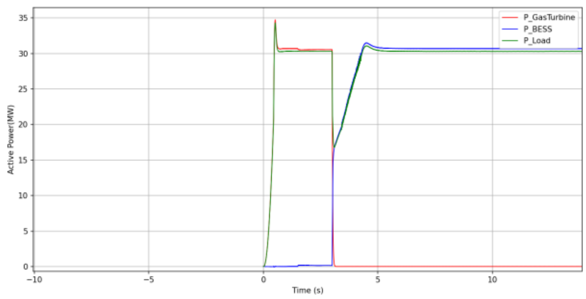


Figure 10. Case 1: Power evolution

- ✓ Voltage and frequency variation. The grid is recovered and controlled by BESS working as *grid- forming* (parallel operation). Microgrid can be sustained over a long period of time while waiting for the gas turbine or any other synchronous generator to recover from a fault.

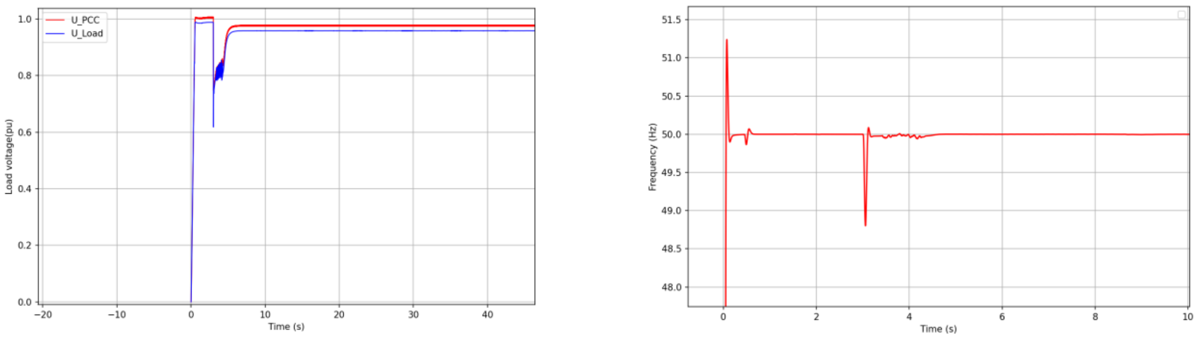


Figure 11. Case 1: Voltage and frequency evolution in simulations

[5] See Annex 1 for further details

BLACK-START

Description[6]

The *black-start* is the ability of the power converter to start to operate during a blackout, i.e. without grid voltage. This feature is deeply linked to islanding mode of *grid-forming* as it has the main purpose of restoring the operation of a power system during blackout by the creation of a grid.

For *black-start* operation it's necessary to provide a secure voltage supply to feed the minimum auxiliary systems that allow the converter to start (power supplies, cooling system…). This external source may be a power line that may come from substation (UPS or external source).

Once the *black-start* operation is successful, the system operates in *grid-forming* mode and other power converters connected to the same grid can start operation in *grid-feeding* mode.

[6] See Annex 2 for an example of grid-forming and black-start operation

ONGRID MODE – PARALLEL OPERATION

Description

In parallel operation, the equipment generates the AC voltage but synchronized with grid voltage, its main purpose is to act as voltage backup and contributes to grid stability, so the plant would remain connected in case of blackout.

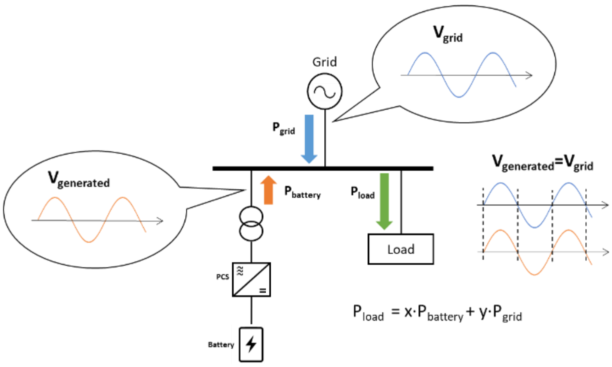


Figure 12. Example of operation in Ongrid mode

Simulation

How Gamesa Electric Proteus PCS works in Ongrid mode during a frequency contingency [7]

The simulation sequence is as follows:

1. The gas turbine is providing the total power demand of the loads (100 MW) while PCSs work in *Ongrid* mode (parallel operation) without injecting active power.
2. A 35 MVA gas turbine trips (partial loss of power generation).
3. PCSs regulate frequency considering both configurations in two separate simulations: *Ongrid* mode and *grid-feeding* with fast frequency response (FFR) functionality when the events occurs.

[7] See Annex 1 for further details

Therefore, two different tests were carried out:

Test 1. Grid-feeding with FFR vs. Grid-forming with FFR

The power response of a BESS with grid-forming is greater and faster than grid-feeding operation, since a system with VSM has greater inertia as well as greater damping. Therefore, in addition to the power that the BESS injects thanks to the P-f droop, another very rapid increase in active power is added due to the contribution of the inherent virtual inertia of the VSM.

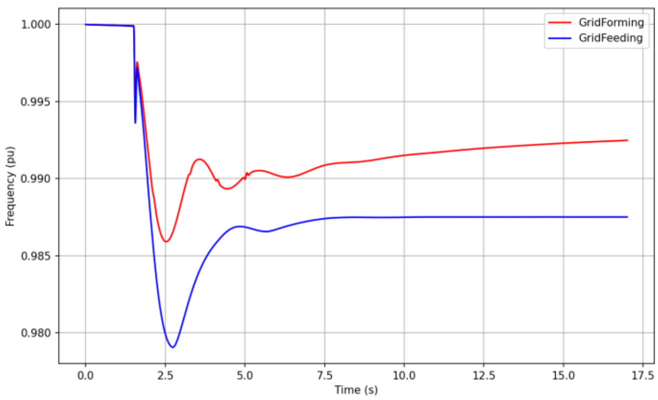


Figure 13. Case 1: Frequency transient at POI in test 1

Test 2. Grid-feeding with FFR vs. Grid-forming without FFR

Despite disabling the P-f droop of the FFR in Grid-forming, the frequency excursion with Proteus PCS operating as a VSM is still smaller than with Proteus PCS operating in grid-feeding mode. The frequency contingency is still damped to a greater extend and more quickly.

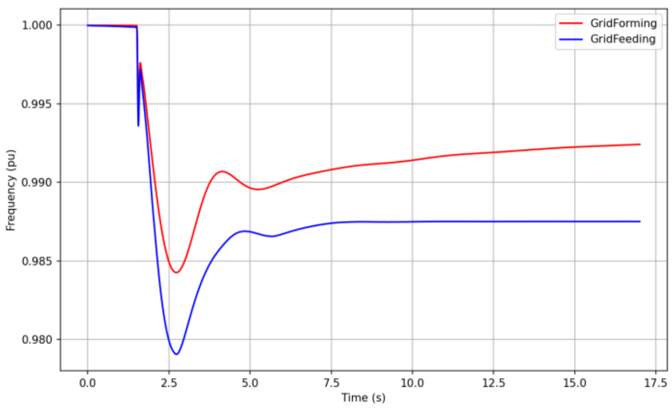


Figure 14. Case 2: Frequency transient at POI in test 2

Shaping New Energy

ANNEXES

ANNEX 1: GRID-FORMING SIMULATION RESULTS

In order to evaluate the performance and stability of grid-forming control algorithms, several simulations have been carried out. Two different cases are shown below where Proteus PCS and Orchestra coexist with loads and gas turbines (synchronous generators) in the same grid.

CASE 1: STABILITY OF ISLANDED GRID

The test consists of demonstrating the stability of an islanded grid governed by BESS working as *grid-forming* when all the synchronous generation trips. The simulated electric scheme and component list are shown below:

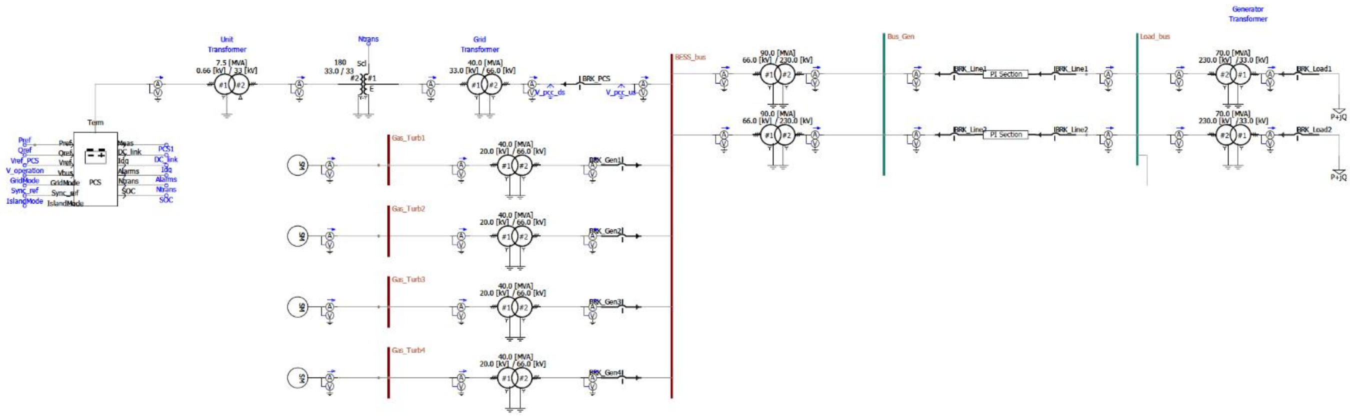


Figure 15. Case 1: Electric scheme

Component	Quantity	Unit power	Total power
Proteus PCS	10	3.75 MVA	35 MVA
Gas Turbine	1	35 MVA	35 MVA
Resistive load	2	15 MW	30 MW
Orchestra	1	---	---

In normal conditions, the gas turbines provide the necessary power to loads whereas the PCS is working as *grid-forming* and would provide the necessary support in case of contingency.

CASE 2: COMPARISON GRID-FORMING VS GRID-FEEDING

The test consists of comparing the different frequency responses obtained with a PCS working in grid-forming (*Ongrid* mode) versus a PCS working in grid-feeding mode during a frequency contingency. The electric scheme and component list are shown below:

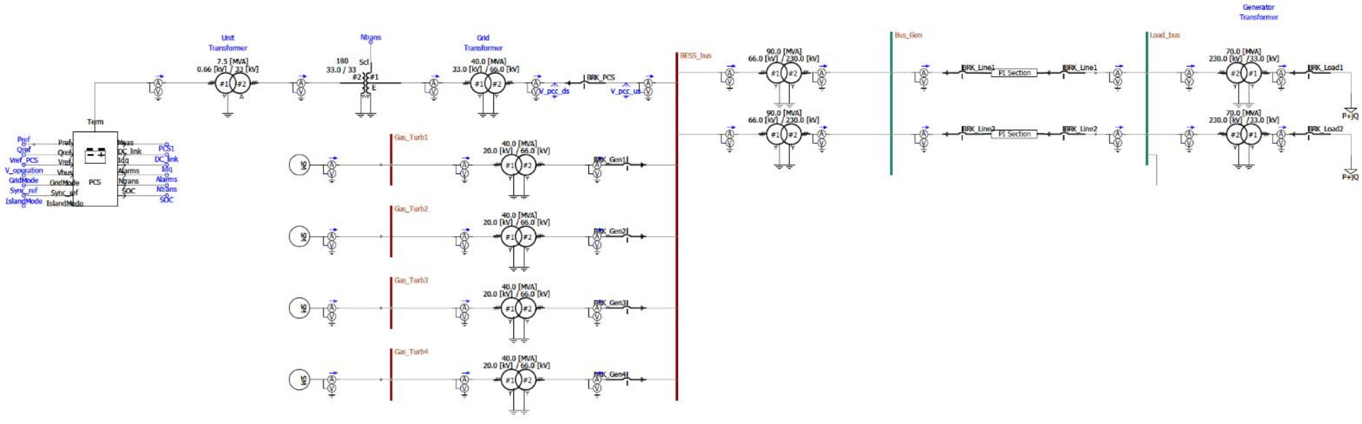


Figure 16. Case 2: Electric scheme

Component	Quantity	Unit power	Total power	Control mode configuration: Power-frequency control at POI
Proteus PCS	10	3.75 MVA	35 MVA	---
Gas Turbine	3	35 MVA	105 MVA	Frequency dead band: 200mHz P-f droop slope: 4%
Resistive load	2	50 MW	100 MW	---
Orchestra	1	---	---	Frequency dead band: 500mHz P-f droop slope: 3%

The gas turbines provide the necessary power to loads in normal conditions whereas the PCS would provide frequency support in case of a contingency. The sequence is as follows:

1. The gas turbine is providing the total power demand of the loads (100 MW) while PCSs work in grid-forming mode (parallel operation) without injecting active power.
2. A 35 MVA gas turbine trips (partial loss of power generation).
3. PCSs regulate frequency considering both configurations; grid-forming in parallel operation (VSM) and *grid-feeding* with fast frequency response (FFR) functionality when the event occurs.

Therefore, two different tests were carried out:

Test 1. Grid-feeding with FFR droop vs Grid-forming with FFR droop

The FFR function of the BESS is tested together with the *Ongrid* mode when the synchronous generator is switched off. In both cases (grid-feeding and grid-forming) there is a droop that performs the same FFR; in case of grid-forming the generator disconnection causes a frequency drop that must be minimized by the BESS, that provides active power to compensate for the power deficit.

The power response of the system by a BESS with grid-forming is greater and faster, since such systems have greater inertia as well as greater damping. Therefore, in addition to the power that the BESS injects thanks to the droop, another very rapid increase in active power is added due to the contribution of the PCS working in *Ongrid* mode. This virtual inertia contribution means that the ROCOF will be less abrupt in the case of a BESS operating in *grid-forming* mode than in a BESS operating in grid-feeding mode.

On the other hand, the turbine control commands the generators to increase their torque. This control is much slower and cannot recover 100% of the frequency, as the inlet valve opening is physically limited.

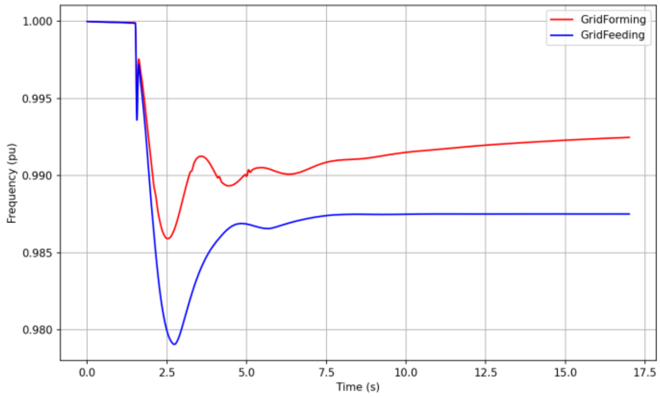


Figure 17. Case 2: Frequency transient at POI in test 1

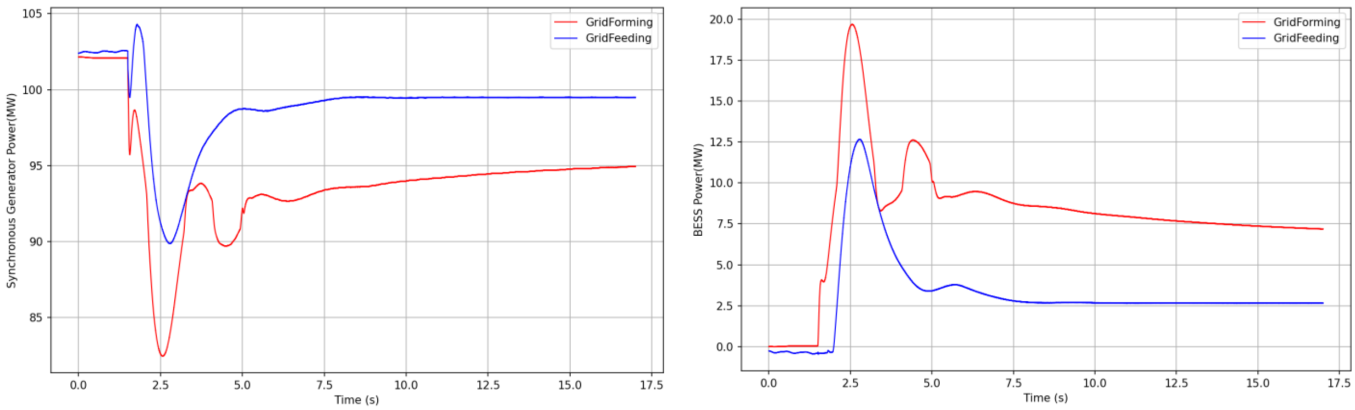


Figure 18. Case 2: Power transient at POI of generators and BESS in test 1

Test 2. Grid-feeding without FFR droop vs Grid-forming with FFR droop

The operation of a BESS with *grid-forming* operation mode is going to be compared against a BESS with *grid-feeding* operation mode, but only the BESS with *grid-feeding* has the FFR P-f droop functionality and the BESS with grid-forming will only have its intrinsic behavior.

Despite removing the FFR droop P-f, the frequency excursion with Proteus PCS operating in grid-forming mode is still smaller than with Proteus PCS operating in grid-feeding mode. The frequency contingency is still damped more and damped faster.

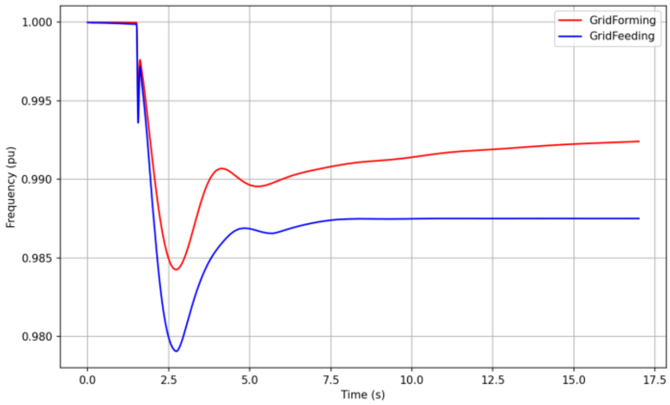


Figure 19. Case 2: Frequency transient at POI in test 2

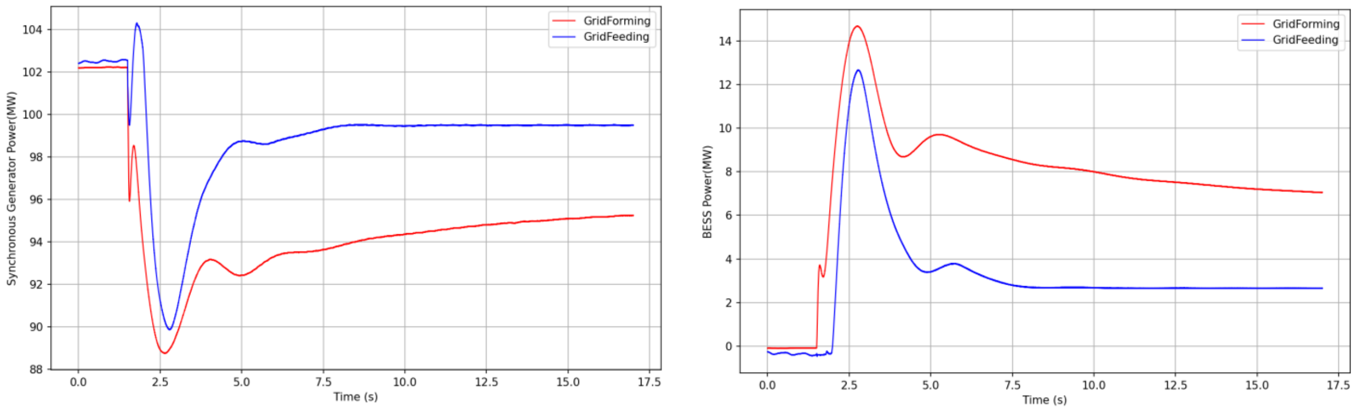


Figure 20. Case 2: Power transient at POI of generators and BESS in test 2

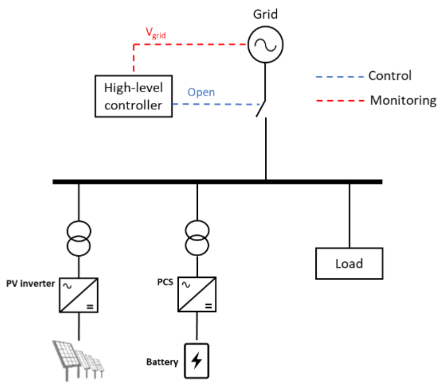
ANNEX 2: EXAMPLE OF GRID-FORMING AND BLACK-START OPERATION

This annex shows an example of how the *black-start* and *grid-forming* functions work. It is considered a grid-tied system composed by Proteus PV inverters, BESS and a load demanding active and reactive power. The BESS has *black-start* and *grid-forming* capabilities and is represented by a single Proteus PCS connected to a battery set, although the example is equally valid for multiple units operating in parallel.

The following describes the system recovery sequence after a blackout. The starting condition considers the initial disconnection of Proteus PV inverter and BESS after the power outage. The complete sequence is as follows:

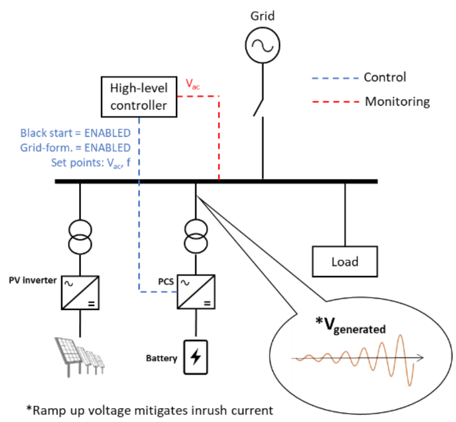
1

Blackout. When blackout is detected by high-level controller, it commands the opening of the main switch; any voltage generated by power plant won´t affect the upstream components (safety issue). By default, all power converters (PV and BESS) stop their operation.



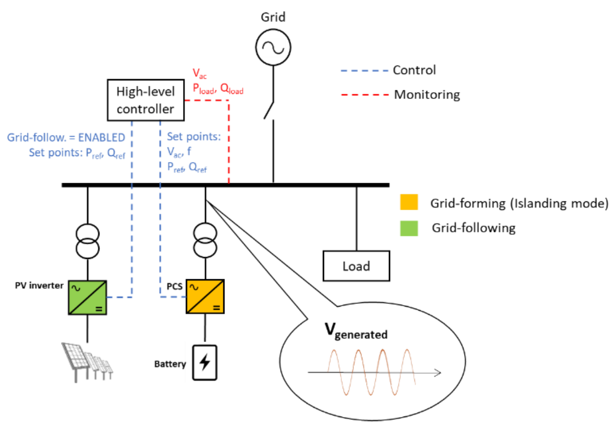
2

Black-start. The controller sends the command to Proteus PCS to enable the *black-start* operation according to voltage set points; amplitude (Vac) and frequency (f). The PCS applies a ramp to the voltage amplitude to avoid current peaks caused by transformer inrush current.



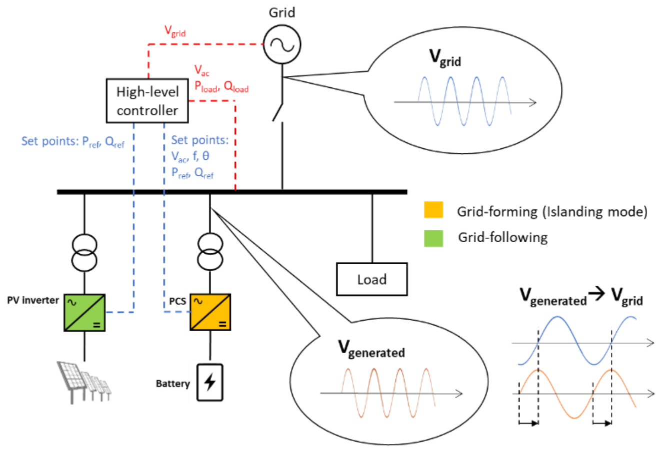
3

Grid-forming (grid creation). The high-level controller sends the start command to Proteus PV inverter to work in *grid-feeding* mode, receiving the active and reactive power set points that are calculated on the load demands. The Proteus PCS works in islanding mode acting as voltage grid creator, additionally it's also able to provide active and reactive power in a similar way to PV inverter.



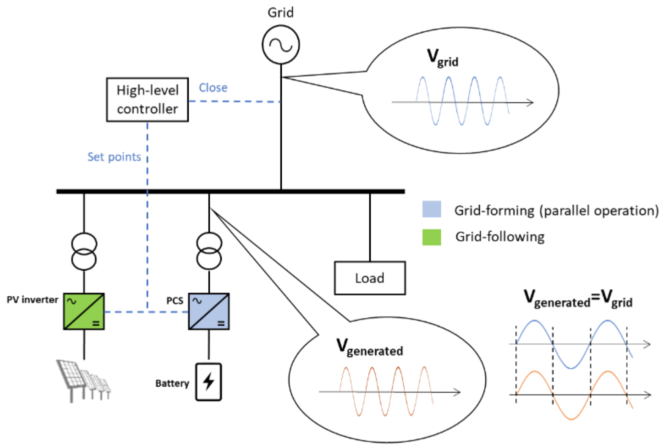
4

Synchronization Once the grid voltage is restored (main switch is still open), the controller adjust the Proteus PCS set points; amplitude (Vac), frequency (f) and phase shifting (θ), in order to synchronize the AC voltage generated by PCS with the voltage grid.



5

Parallel operation. When both grid voltage and generated voltage by Proteus PCS match (no possibility of short circuit), the high-level controller closes the main switch. The PCS now works in parallel operation; it generates AC voltage in presence of grid voltage. At the same time, both Proteus PV inverter and PCS continue receiving power set points from the controller.



ANNEX 3: SYNCHRONOUS GENERATORS

How it works

A synchronous generator (also called *alternator*) generates electricity due to principle of magnetic induction; an electromotive force is induced in a coil (stator) as a result of a coil passing through a magnetic field which is generated by a rotating shaft (rotor). The addition of different coils at stator allow to generate waveforms with different phases (single-phase, two-phase or three-phase).

Synchronous generators are characterized by the fact that the magnetic field generated in the rotor produces an alternating current with a frequency synchronized with its speed, where it exists a direct relation between the rotor mechanical speed and the frequency according to next relation:

$$f = \frac{p}{120} n$$

f is the electrical frequency (Hz)
p is the number of poles
n is the rotor speed (rpm)

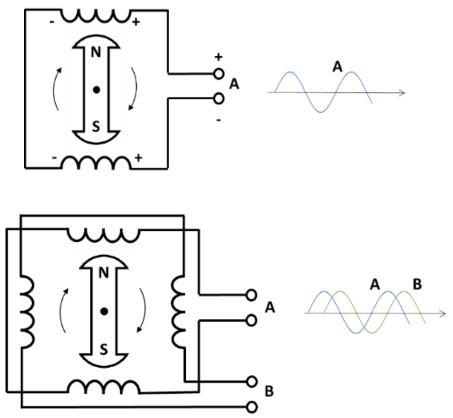


Figure 21. Simplified scheme of single-phase and two-phase generator

In case of grid-connected generators, the rotatory speed is conditioned by electrical frequency, for example a 2-poles alternator rotates at 3000 rpm on a 50 Hz grid (Europe) or at 3600 rpm on a 60 Hz grid (North America).

Power versus frequency

In synchronous generators the generated power depends on rotor mechanical speed and decreases as load demand increases, the relation is defined by the generator *dropping characteristic* curve, as shown below.

Hence, since there is a direct relation between mechanical speed and frequency, dropping characteristic curve can be also extended to frequency. This is also called *statism*; percentage of frequency (or speed) variation divided by percentage of power output variation.

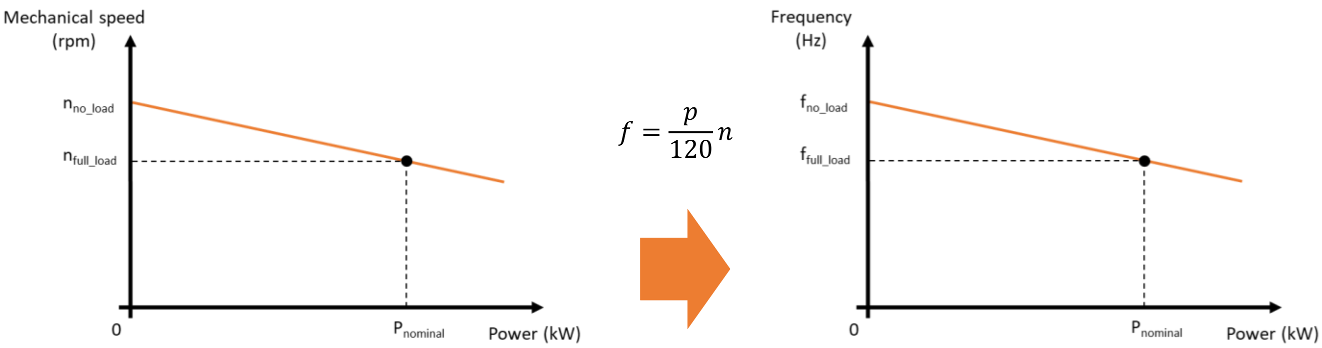


Figure 22. Dropping characteristic curve; statism

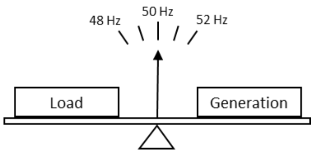
However, under real conditions the grid frequency is not a fixed value and changes slightly according to load fluctuations, these variations usually move in a very small range, typically less than 0.5 Hz (generator speed changes about $\pm$30 rpm for 50 Hz grid), to avoid grid instabilities. Here, synchronous generators play a very important role in controlling the grid stability; they are responsible for responding to these variations by modifying their power in order to restore the frequency to the nominal value.

ANNEX 4: GRID FREQUENCY CONTROL

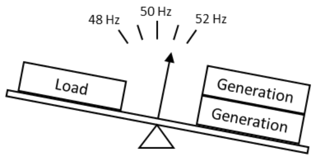
BALANCE OF POWERS

Frequency control must be present to ensure a stable grid, large variations from the nominal value may lead to load malfunctions or increased losses, especially if loads include electrical machines specifically designed to operate at a precise frequency (pumps, fans, transformers…).

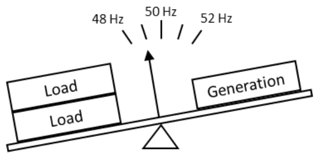
Grid frequency is controlled as long as there is a balance between power generation and loads demand (*generation-consumption*), because shaft speed is the result of the balance established by shaft mechanical torque and the opposite electrical torque created in stator coils, if the power load decreases the electrical torque will be lower than mechanical torque and rotating speed increases, by the same way, if the load demand increases shaft speed decrease, there are 3 possible scenarios:



Balanced; When generated power is equal to consumed power by loads (discounting the losses), frequency is maintained at nominal value.



Over-generation: When the generated power is greater than loads demand, the grid frequency increases (over-frequency).



Under-generation: When the generated power is lower than loads demand, the frequency decreases (under-frequency).

FREQUENCY CONTROL BY SYNCHRONOUS GENERATORS

Power generation based on large rotative machines has to adapt their output power (shaft speed), depending on the changing variations of frequency grid. But any change in shaft speed is not instantaneous, massive shafts have mechanical inertia that dampens any speed variation (several tons rotating at high speed).

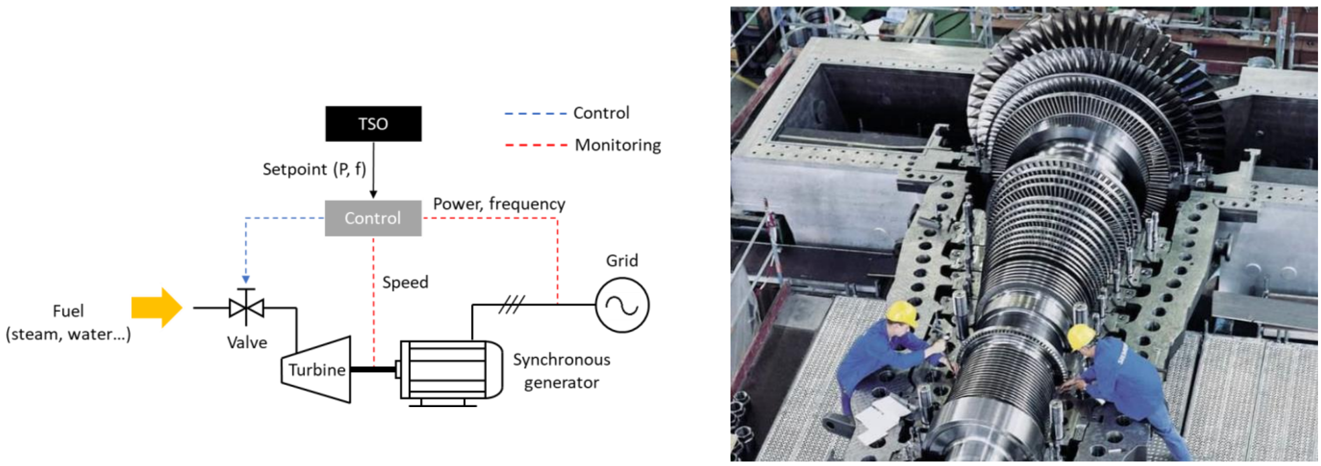


Figure 23. Generic frequency control in synchronous generator (left). Rotatory shaft of Siemens steam turbine SST-900; up to 250 MW rotating at 3000 rpm (right)

As the grid frequency is linked to active power, generators need a closed-loop control system that allows to regulate the output power; for one side, the system acts directly on the turbine intake valve and regulates the fuel flow[8], and secondly the TSO monitors the grid status and calculates the setpoints in each case, this closed-loop control makes possible to manage the generated power (and thus the frequency), according to changing grid conditions.

Another factor to consider is the response speed, as different generators will respond at different speeds; for example, coal-fired plants react slower than hydropower plants, any stable grid combines multiple power sources in order to cover the needs of any possible scenario.

TIMING IN FREQUENCY CONTROL

Due to the grid dynamics, where load demand continuously changes, the grid operator must carry out frequency corrections in order to ensure the grid stability. Further, as it is stated in the previous section any change of frequency is not instantaneous due to presence of massive generators whose mechanical inertia provides a dumping (inertial response) that limits the rate of change. The quantity that measures this inertia (frequency change after imbalance between generation and load) is known as *ROCOF* (Rate Of Change Of Frequency), calculated as the derivative of the frequency with respect to time $\left(\frac{df}{dt}\right)$. Large *ROCOF* values may cause the grid destabilization due to mechanical limitations of the active generators; if they are not able to keep the frequency variation speed under control some protection could be triggered.

In a second stage, frequency corrections are classified according to the time scale, i.e. the time needed for the system to provide a response[9]; primary, secondary and tertiary.

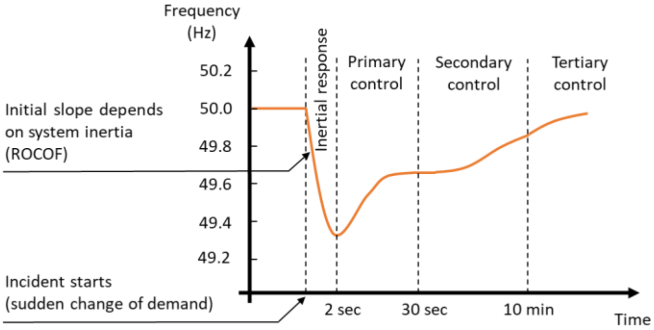


Figure 24. Frequency control timeline (timing is indicative)

[8] Fuel flow may vary according to the turbine type; hydroelectric plants regulate the water flow, gas-fired plants regulate the gas input and so on
[9] Timing response considered in classification below may change according to the author

Primary control

It is the fastest one and operates in range between 2 to 30 seconds to compensate the generation-consumption imbalance ($P_{generation} = P_{consumption}$), the local control autonomously acts directly on the turbine inlet (see Figure 27) and the response time is conditioned by shaft mechanical inertia and its initial speed.

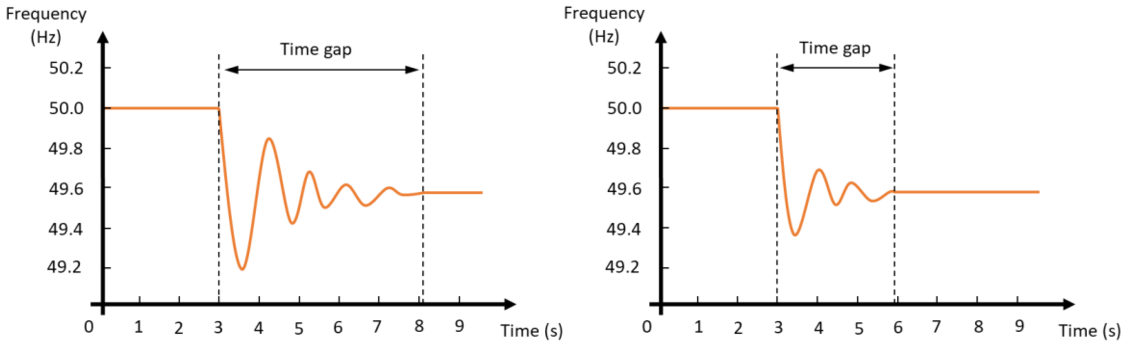


Figure 25. System frequency change without primary control and with primary control

As an example, consider a generator with the *statism* characteristic curve indicated in the figure below operating at point A (power and frequency are defined by P_A and f_A); after a load demand rising what means an under-generation condition, the frequency is reduced due to generation-consumption imbalance (from f_A to f_B), so in order to recover the balance the control increases the generator power according to its *statism* feature (from P_A to P_B).

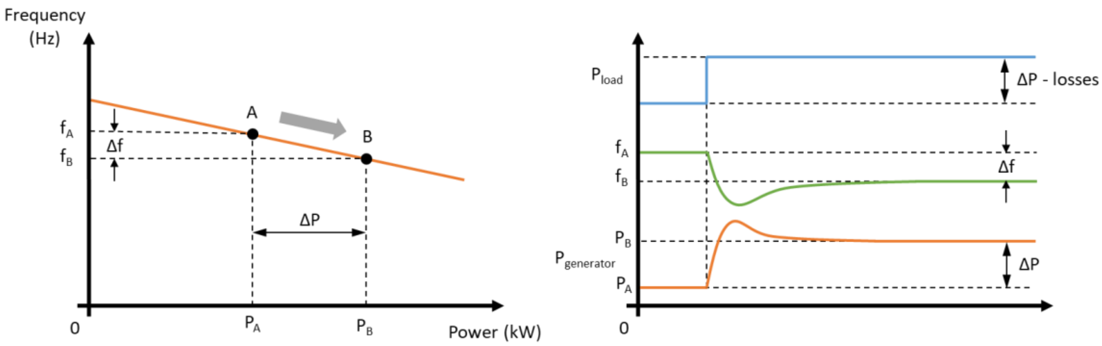


Figure 26. Primary response of single generator

Primary control may be applied to individual units or a small group of generators (generator 1 and 2 in next figure). Here, each unit will modify the rotating speed providing a new output power according to its statism feature (ΔP_1 and ΔP_2), similarly the power transient of each unit (overshoot) also depends on its shaft inertia.

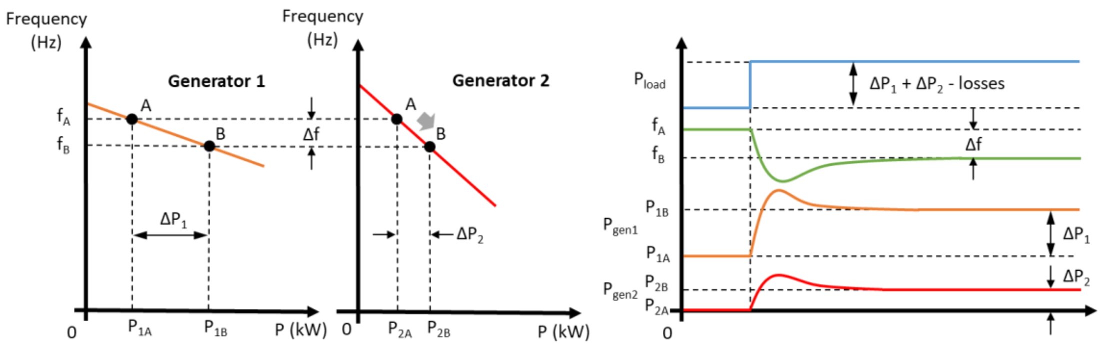


Figure 27. Primary response of 2 generators with different statism

Secondary control

It operates from 30 seconds to 10 minutes. After a change in load demand, the frequency is automatically adjusted during the first seconds (primary control), then the secondary control comes into operation to restore the frequency to the nominal value by modifying the system generation power. This control is performed by TSO which also balances the power between different generators in order to avoid possible overloads.

The TSO modifies the power setpoint of each generator by acting on turbine intake valve (steam, water, gas…) until restoration of frequency (f_A), this is equivalent to shifting the generators drooping characteristic curve (moving from B to C in next figure).

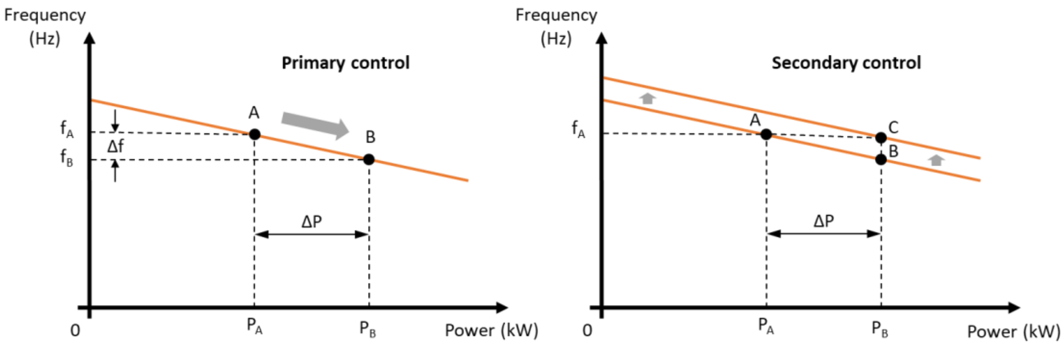


Figure 28. Complete restoration of nominal frequency after change of load demand; combination of primary and secondary response

This control cannot be applied individually, otherwise generators would compete separately for frequency adjustment and the system would be unstable. The TSO centralizes the frequency measurement, makes the necessary calculations and send the power setpoints to all generators involved, this control loop is called *AGC - Automatic Generation Control*.

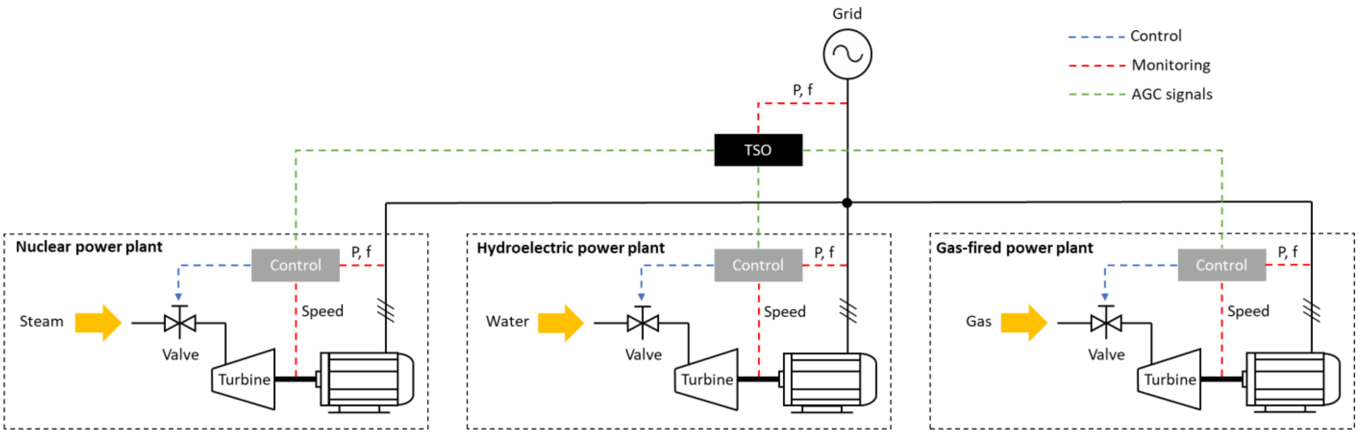


Figure 29. Scheme of control by AGC

Tertiary control

It operates from 10 minutes onwards. The aim consists of ensuring an energy reserve necessary for future frequency control. Secondary control is only effective if there is enough energy reserve in the system, the TSO adjusts (by AGC signals) the operating programs of different generators in order to fulfill the future demand and to optimize the costs in generation.

ACRONYMS

AC – Alternating Current

AGC – Automatic Gain Control (TSO control signal)

BESS – Battery Energy Storage System

BMS – Battery Management System

CCUS – Carbon Capture Use and Storage

DC – Direct Current

DOD – Depth of Discharge (%)

f – Grid frequency (Hz)

FFR – Fast Frequency Response

FR – Frequency Response

FRT – Fault Ride Through

GaE – Gamesa Electric

HIL – Hardware In the Loop

HVRT – High Voltage Ride Through

I – Current (A)

IEA – International Energy Agency

LVRT – Low Voltage Ride Through

masl – Meters above sea level

n – Generator rotation speed (rpm)

p – number of poles

P – Active power (W)

PCC – Point of Common Coupling (same as POI)

PCS – Power Conditioning System

PF – Power Factor

PFR – Primary Frequency Response

POD – Power Oscillation Damping

POI – Point of Interconnection (same as PCC)

p.u. – per unit

PV – Photovoltaic

Q – Reactive power (VAR)

ROCOF – Rate Of Change Of Frequency

rpm – Revolutions per minute

S – Apparent power (VA)

SI – Synthetic Inertia

SOC – State of Charge (%)

SOH – State of Health (%)

TSO – Transmission System Operator

UPS – Uninterruptible Power Supply

V – Voltage (V)

VRT – Voltage Ride Through

VSG – Virtual Synchronous Generator

VSM – Virtual Synchronous Machine

Θ – Phase shift

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