The Hybrid Power Plant in Graciosa Island - a Pioneer Project in the Azores Islands

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Abstract **- Graciosa Island belongs to the Azores archipelago (Portugal) located in the middle of the Atlantic Ocean. It was the chosen place by a private investor to build a pioneer project in the Azores: the first hybrid power plant (HPP) that includes a wind farm, a solar PV, and a battery energy storage system. These generation assets, together with the utility's main Diesel power plant, are controlled by an advanced Energy Management System (EMS). This hybrid power plant has been operating since August 2019 and the aim of this paper is to describe the evolution of this project in terms of the hybrid power plant performance in the context of an ambitious plan for Graciosa´s progressive decarbonization.**

Wind power plant; Hybrid power plant; Battery energy storage system; Photovoltaic power plant; Renewable Energy; Energy Management system

I. INTRODUCTION

Graciosa Island belongs to the archipelago of the Azores (Portugal) with an area of 60,65km2 and has around 4300 inhabitants.

In the end of 2018, the HPP developer (Graciólica) installed the final configuration of the HPP. After a testing phase that lasted some months with the local system operator (EDA), the HPP began its commercial operation in August 2019. The HPP introduces a new paradigm in the way a small island can run its power system relying mainly on renewable energy sources combined with storage solution.

II. GRACIOSA ISLAND POWER SYSTEM OVERVIEW

In April 2022, Graciosa Island generation power system is being composed by two main electricity sources:

1- Conventional thermal power plant (DPP), with a total installed power of 4.7MW (5.9MVA), being these six diesel groups connected to a common 15kV busbar.
2- The recent hybrid power plant (HPP), which is thoroughly described in the next chapter.

According to the 2021 annual report of the system operator (EDA), the electricity produced in Graciosa by these two sources reached 13,55GWh, with the HPP accountable for 65% of annual electricity consumption. The remaining 35% was provided by the conventional DPP. The maximum peak consumption was registered in December at 2,36MW while the minimum (valley hours) was registered in March and September with 0.97MW. In following Figure 1 the share of electricity generated is depicted per month and per energy source, in 2021.

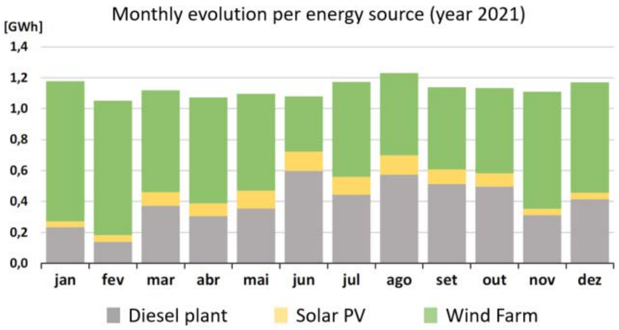

Figure 1: Electricity generated in Graciosa per source in 2021 [1]

III. GRACIOSA HYBRID POWER PLANT

As many other islands across the world, Graciosa relied mainly on a diesel power plant (DPP) to supply electricity and to stabilize the island grid. The integration of the HPP into the existing grid ended the dependency on diesel engines for frequency and voltage regulation, since the BESS has a grid forming operation mode, either standalone or in parallel with running diesel engines. The BESS can adjust its power output on a millisecond basis, providing a very effective response to large output power swings from the renewable sources. Consequently, the frequency and voltage are maintained very close to their nominal value. It maximizes the penetration of wind and solar power into the grid up to 100% of the island load demand, when their power output matches or surpasses the island load. It also provides short-circuit current capabilities to clear any fault on the grid.

The design and commissioning phases of the project were followed very closely by the local system operator. Their expertise on the field had a major contribution to the development of unique EMS control algorithmics that contributed to a smooth transition from the previous diesel power plant operation concept to the hybrid one.

The single line diagram (SLD) of Graciosa hybrid power plant is presented in Figure 2 and consists of the following units:

- 4,5 MW Wind Power Plant (5x 900 kW)
- 1 MW PV Power Plant
- 7,425 MW Battery Power Plant/Battery Energy Storage System (3x 2475 kW) with a usable capacity of 2,6 MWh
- Autonomous EMS
- 4,6 MW Diesel Power Plant (3x 600 kW, 1x 810 kW, 2x 1000 kW)

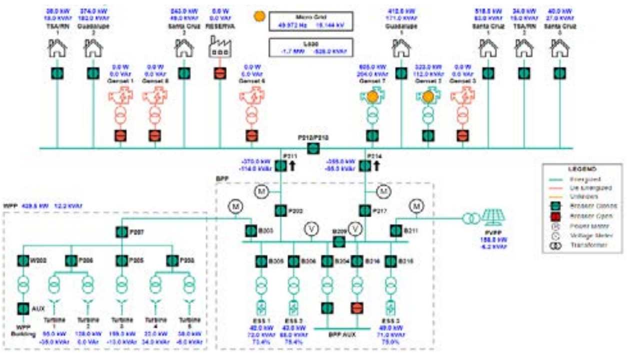

Figure 2: SLD of Graciosa hybrid power plant [2]

a) Wind power plant

The wind power plant comprises five wind turbines from Enercon type E-44 with 900 kW of power each, totaling 4.5 MW. The role of the wind farm is to be the main source of energy. Each WEC integrates inside the tower a 1100 kVA 0,4/15 kV transformer.

i. Wind energy converters

The WECs installed include the standard electrical configuration of ENERCON wind energy converters (WECs) with its direct-drive and full converter concepts. The ENERCON FACTS (Flexible AC transmission system) technology allows the WECs to provide important features to the grid, such as:

-Reactive power capability: each E-44 WEC has a potential to provide up to 630 kVAr of nominal reactive power, in both directions (inductive and capacitive), as represented in Figure 3.

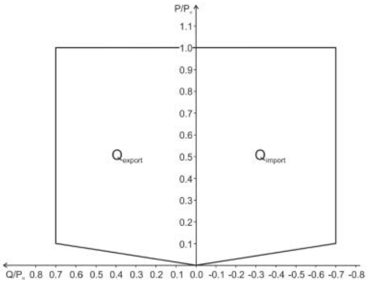

Figure 3: PQ diagram of the Enercon E-44

-Fault ride through: these WECs are equipped with fault ride through (FRT) capability. This feature allows the WEC to stay connected to the grid, up to a maximum of 5 seconds, during undervoltages or overvoltages in the grid. Moreover, during a voltage dip the WEC can be configured either to not inject any current or to inject capacitive reactive current proportional to the voltage dip.

-ENERCON Storm Control: makes these E-44 WECs well suitable for isolated systems with very demanding wind conditions. The ENERCON storm control system allows the WEC to keep generating at reduced active power levels in the event of extreme high wind speeds in the range of 25-38 m/s. The power injected at 38m/s is zero. As soon as the wind speed decreases below 38m/s the WEC ramps up again. For safety reasons the WEC shuts down in case of wind speeds above 40m/s. [3]

ii. Wind power plant controller

The monitoring and control regulation of the Wind power plant is performed by means of the ENERCON SCADA Server and the ENERCON Farm Control Unit (FCU).

The ENERCON SCADA Server is an industrial computer used to store and monitor the wind farm data. Every 24h a data replica is stored in an ENERCON server in Germany. For communication purposes, it exchanges online data and control setpoints with Graciólica´s EMS. The ENERCON FCU is an advanced wind farm controller, equipped with a grid analyzer and a PLC (programmable logic controller). It has the task to measure the relevant electrical variables at the point of connection of the wind farm and control them based on predefined control settings or from setpoints received from the EMS. In this way, the FCU establishes a closed-loop control between the WECs and the 15kV substation, which is the predefined point of connection (PoC).

b) PV Power plant

The PVPP consists of 4000 photovoltaic panels and 40 inverters. The photovoltaic panels are installed in strings of 18 and 23 panels in series and connected on the DC side of the inverter in parallel. The inverters operate in zero power mode and therefore do not inject any short-circuit current during faults. The AC cables of the inverters are connected to a powerhouse that hosts a power transformer to step-up the voltage up to 15 kV. The main PVPP feeder is connected on the BPP substation dedicated cubicle. The PVPP electrical layout is presented in Figure 4.

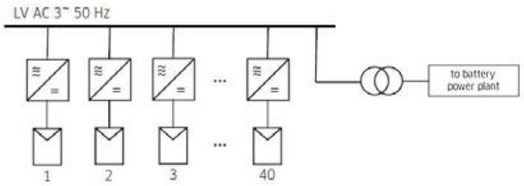

Figure 4: PVPP electrical layout

c) Battery Energy Storage System

The BESS consists of individual lithium titanate oxide (LTO) cells with a nominal capacity of 30 Ah measured at 0,1C discharge rate and a nominal voltage of 2,3 V. Each cell has an expected lifetime up to 15000 cycles, at 1C charge/discharge full depth of discharge and 20 years of expected calendar life. The recommended charge current is of 30 A (1C) although the maximum charge current can go up to 120 A (4C). Likewise, the recommended discharge current is of 30 A (1C) and the maximum discharge current of 120 A (4C). The maximum discharge and charge temperature range varies between -20 Celsius degrees and 55 Celsius degrees. The cell lifetime characteristics are presented Figure 5.

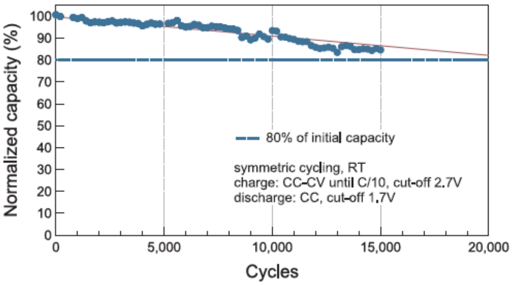

Figure 5: Lifetime characteristics (4C charge / discharge) [3]

The main advantages of the LTO cell technology are:

- Excellent lifetime characteristics
- High charge/discharge rates
- Superior safety features
- Wide temperature range
- Symmetrical system design

In total, the BESS comprises 40 battery racks, 760 battery modules and 45600 LTO cells. The battery module architecture consists of 60 cells, 3P20S.

Another key unit of the BESS is the grid-forming power converter system (PCS) which operates with frequency and voltage droop curves that emulate the behavior of a diesel engine, allowing parallel operation of the converters with the engines. When the converter is loaded with active power, the frequency is reduced, and vice versa. The same principle is used to control the voltage by managing the reactive power flow. The converters are also equipped with a DC Precharge that enables the black start of the island load feeders, if necessary. Nevertheless, it was agreed with local system operator that the diesel engines are the first units to perform black start, following the synchronization with the PCS units.

Concerning the PCS short-circuit current (Icc) capability, it should be noted that these units were tuned to provide an Icc up to 1,5 times their rated current (In) over 600 milliseconds, being the value reduced up to 1,25xIn for an additional 4 seconds. They contribute to any type of fault (line-to-line, line-to-ground, three-phase) within the mentioned time frames. When the PCS units are running in standalone, at least two units are always connected to grid, to comply with the minimum short-circuit requirements.

i. BESS response to transient events

When transient events occur on the grid, a coordinated response between the BESS and the EMS is necessary to ensure that the frequency and voltage are recovered to their nominal values as soon as possible. During short-circuit events, only the DPP and BESS provide short-circuit current to clear faults. The solar and the wind farm were set to operate in zero power mode, and therefore do not inject any fault current. Figure 6 presents a HPP scenario of operation on September 23rd, 2020, where the island load is covered by the renewable sources (wind and solar plants) with no diesel engines running.

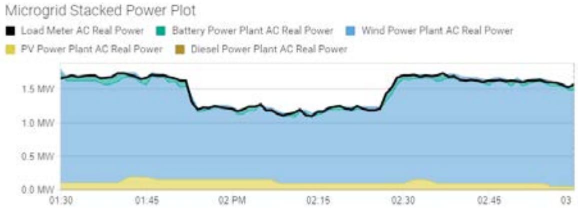

Figure 6: phase-to-phase short-circuit event on grid

Slightly before 2 pm, a phase-to-phase short-circuit at one of the island load feeders was detected, causing a load drop of 500 kW. The correspondent feeder tripped offline following a successful fault clearance. Figure 7 presents the frequency dip that reached 47,4 Hz while Figure 8 presents the voltage dip that reached 2,8 kV and 3,4 kV, on phase B and C, respectively. As it is seen through the frequency and voltage graphs, a fast and synchronized response among the BESS and EMS enabled the frequency and voltage to be restored within 300 milliseconds.

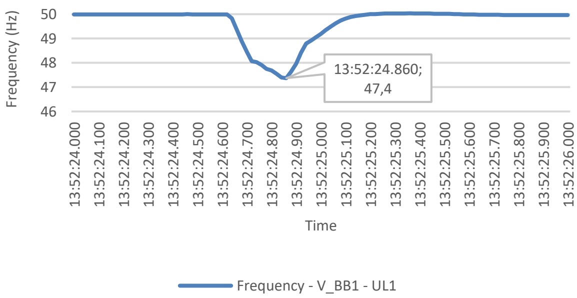

Figure 7: Frequency measured at BPP busbar during short-circuit event (sampling rate of 256 per cycle)

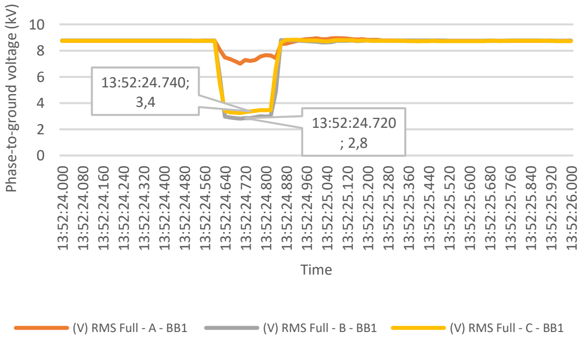

Figure 8: Phase-to-ground voltage measured at BPP busbar during short-circuit event (sampling rate of 256 per cycle)

d) Energy Management System

The dispatch of the assets is performed by an autonomous Energy Management system (EMS) which does not require manual interaction from the plant operator. The EMS communicates with interfaces located downstream at each individual plant so that an effective system control can be achieved without jeopardizing the safety of the grid. Different layers of control are used for different system purposes. The EMS receives operating status updates and issues a wide variety of operating setpoints. Communication loss strategies were also designed and implemented between the EMS and those interfaces to ensure that the island grid remains safe and resilient when communication loss events occur.

The EMS was designed to ensure a stable operation of the grid while maximizing the renewable penetration. The main objectives of the EMS are [4]:

1. Maintain grid stability and security of supply (N-1)
2. Maximizing renewable penetration by forecasting load and renewable generation
3. Minimizing DPP operating costs
4. Enhancement of power quality

The objectives of the EMS [4] shall be achieved by considering the following diesel engines restrictions imposed by the local system operator:

- Power factor requirements
- Voltage and frequency operating range
- N-1 operation criteria
- Active and reactive power loading steps
- Minimum stop and run time
- Daily number of individual engine starts
- Daily number of total engine starts

IV. HYBRID POWER PLANT PERFORMANCE RESULTS

The HPP went online in August 2019 following a successful phase of commissioning tests. The most relevant HPP operation indicators are presented in Table 1 for the first two years and seven months of operation, since August 1st, 2019, until March 1st, 2022.

Table 1: HPP operation indicators

HPP operation indicators	1st August 2019 – 1st March 2022
Full connection of HPP to island grid (days)	934
Renewable penetration (%)	60,0
Island load (GWh)	34,7
Cumulative days operating with 100% renewable penetration	338
Net renewable energy (RE) delivered to grid (GWh)	21,4
Net solar energy delivered to grid (GWh)	2,46
Net wind energy delivered to grid (GWh)	18,91
Average wind speed (m/s)	8,2
Average irradiation (w/m^2)	320,7
BESS AC energy charged (GWh)	1,94
BESS AC energy discharged (GWh)	1,71
BESS AC round-trip efficiency (%)	80
DC average battery cycles/day	0,83
Technically available RE curtailed (GWh)	14,5
Monthly average number of engines starts	54
Monthly average of engines running time (hours)	982
Running engines loading level average (%)	66
CO2 emissions avoided (tons)	14864

It should be highlighted that over the first two years and seven months (942 days) of commercial operation, the HPP was fully functional with its assets connected to the island grid over 934 days, representing an uptime of 99,2%. It achieved a renewable penetration of 60%. Moreover, the island load was exclusively supplied from renewable sources for the equivalent of 338 cumulative days, which represent 36% of the analyzed period. In total, 21,4 GWh of renewable energy was delivered to grid, of which 88% was produced from the wind farm and 12% from the solar farm.

Concerning the BESS unit's usage, 1,94 GWh were charged while 1,71 GWh were discharged, representing an AC round-trip efficiency of 80%. The measured DC cycles per day was of 0,83.

The 14,5 GWh of technically available RE curtailed should be emphasized as it represents 68% of the net RE delivered to grid. This technically available RE was mostly curtailed in periods that the state of charge of the ESS units is at the highest, and the island load is already supplied at 100% from the renewable sources. The 4,5 MW wind farm plus 1 MW solar farm, versus the 2,3 MW of island peak load, contributes to a significant amount of technically available RE that ends up not being used.

Regarding the operation of the diesel engines, which are fully controlled by the EMS, an average of 54 engine starts per month was observed, that represent 1,7 engine starts per day. The engines ran on average 982 hours per month at a loading level of 66%.

A comparison for the diesel engine's operation main indicators is presented in Table 2 for 2018, where there were only diesel engines running on the island grid, whereas in 2021, where the HPP was already in full operation. The liters of diesel consumed on the DPP for the two years of analysis were also quantified.

Table 2:DPP operation indicators

	2018 (Diesel Engines)	**2021 (with HPP)**
Liters of diesel consumed (million)	3,4	1,4
Average of engines daily starts	2	1,8
Total engines running time (hours)	23629	10373
Running engines loading level (%)	70	65

In terms of diesel consumption, two million liters of diesel were saved comparing to 2018 and 2021. In 2021, the engines daily starts were reduced by 11% while the running time was reduced as well by 127%. The engine's loading level was reduced by 7%, being the only indicator that has not been improved. Unlike the remaining indicators, the loading level is intended to be kept as high as possible to maximize the diesel engine´s efficiency.

V. POWER QUALITY ENHANCEMENT

The power quality (PQ) has been considerably improved since the HPP went online. Figure 9 and Figure 10 present the frequency and voltage profile at the DPP busbar before and after the connection of the HPP to the island grid. The moment in time where the frequency and voltage become more stable, represent the moment of synchronization of the BESS units with the diesel engines. Different control layers of the EMS also support the BESS units to maintain these parameters as close as possible to their nominal values.

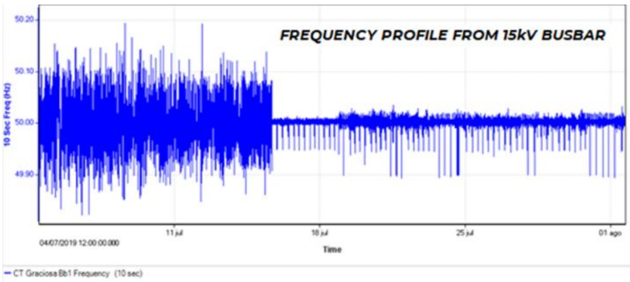

Figure 9: Frequency profile at DPP busbar [4]

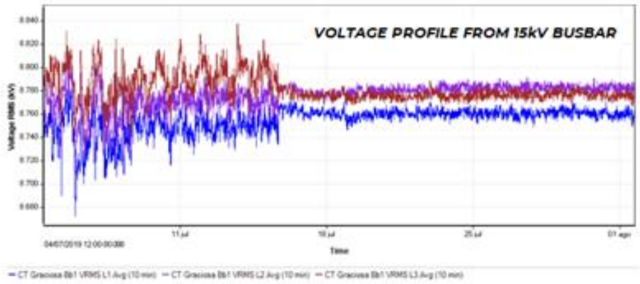

Figure 10: Voltage profile at DPP busbar [4]

A PQ parameters comparison based on the EN 50160 is presented for six months of operation from August 1st, 2017, until January 31st, 2018, versus the entire commercial operation period of the HPP, from August 1st, 2019, until March 1st, 2022. The parameters were collected by a class A PQ measurement equipment connected at the DPP busbar. For the mentioned periods of analysis are assigned the following assets:

- August 1st, 2017, until January 31st, 2018: **Diesel Engines**
- August 1st, 2019, until March 1st, 2022: **HPP (EMS, BESS, PVPP, WPP, DPP)**

The frequency and voltage are presented in Figure 11 and Figure 12. As per the EN 50160, the frequency minimum and maximum limits are 49 and 51 Hz, respectively. The voltage limits are 13,63 kV and 16,6 kV. The island operating voltage set by the DSO is 15,15 kV.

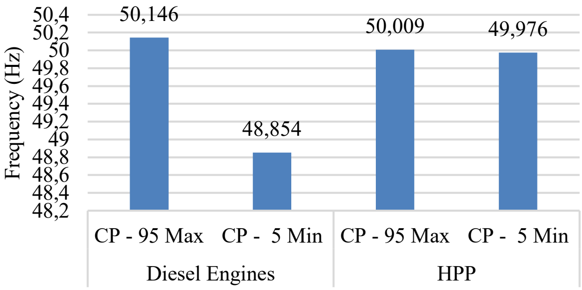

Figure 11: Frequency measured as per EN 50160

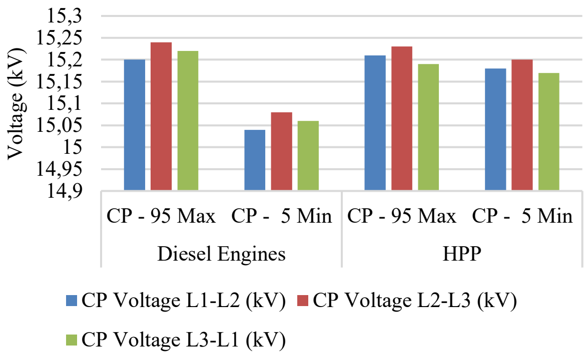

Figure 12: Voltage measured as per EN50160

It is notable that the voltage and frequency are kept farther from the EN 50160 max and min limits after the connection of the HPP to the island grid, being thus improved those parameters. The remaining PQ parameters, including THD, unbalance and flicker Plt are presented in Figure 13. These have also been significantly improved apart from the flicker Plt. However, the flicker measured percentage remains quite far from the EN 50160 limit.

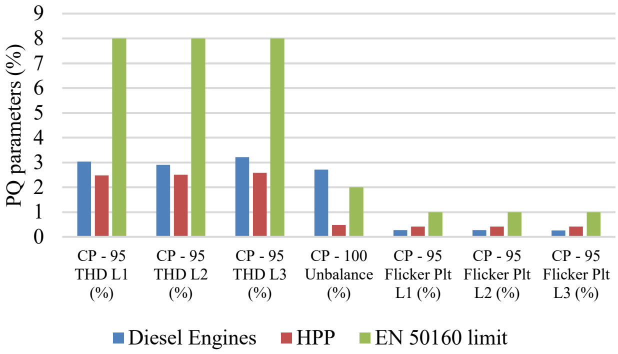

Figure 13: THD, unbalance and flicker Plt

VI. NEXT TARGETS AND CHALLENGES

The HPP operation performance results obtained so far are within the initial expectations of this project, which aims to reach an island renewable penetration rate between 60 and 65 percent, on a yearly basis. The numbers presented in this paper show an achieved renewable penetration rate of 60 percent in the first two years and seven months of commercial operation, matching the initial project expectations. If only 2021 is considered, the penetration rate of the HPP was 65%.

If more ambitious targets of renewable penetration are to be achieved, different strategies can be implemented. Firstly, a greater relaxation of the constraints associated to the diesel engines operation should be considered. On one hand this strategy may cause higher maintenance and operation costs with the diesel engines, on the other hand it should be significantly less than the cost of the diesel consumption that would be avoided. This would be the cheapest option, and the most easily achieved in a short time horizon, though the increase of renewable penetration could be limited.

Secondly, the integration of an additional renewable source in the HPP may be considered mostly for periods where there is no significant power production from the wind and the solar farm. An example of this could be another controllable RE generator such as a biomass plant. This option would be significantly more expensive but result in a larger amount of RP in comparison with the first option.

Thirdly, the practical use of the 14,5 GWh of technically available RE curtailed so far in the HPP. One way to achieve this would be to increase the capacity of the BESS or by adding another energy storage technology to the HPP. This would result in a larger quantity of the curtailed energy being stored and used later, further offsetting use of the engines. The only issue with this approach is the reduced economic viability of any battery extension due to lower utilization when excess energy is unavailable.

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