Impact of a Battery Energy Storage System in a 100% renewable network.

Case study of Brava Island.

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***Abstract*—With the growth in energy demand that has recently occurred accompanied by the increasing of renewable energy penetration, the biggest challenge to the electrical networks is to meet this development in a safe, economical and sustainable way. Energy Storage Systems (ESSs), and specifically Battery Energy Storage Systems (BESSs) have proven to be crucial elements in this paradigm change by contributing to increase the renewable penetration and by mitigating the operational problems that arise from it. The Brava Island, in Cape Verde, presents a renewable energy plan to 2020, which aims to turn the island generation 100% renewable with the help of a BESS. Thus, the objective of this work is to study the possibility of operating the island network in 2020 with only renewable generation and a BESS, analysing the system stability. For this, the simulation scenarios including the forecast of load and renewable resources for 2020 were built. The sizing/implementation of the network is done in PSS/E software. To draw the necessary conclusions from this study, stationary and transient studies are carried out. The analysis of the results shows the dependence between the BESS and the stability of the network, given the importance it showed in primary frequency control and providing flexibility to the grid. Besides, there were also presented studies that offer a picture in which there is the aid of the smaller conventional machine of the island.**

***Index Terms*—Brava Island, 100% Renewable Project, EES, BESS, PSS/E**

I. Introduction

NOWADAYS, the developing countries are leading the rise in electricity demand largely because of the fast population growth that they present. In addition to this energy development, some questions arise about the dependence of fossil fuels (coal, gas and oil) as primary energy source and the harmful consequences from the environmental, economic and geopolitical point of view. In the last decades, all this factors have contributed to many organizations, like United Nations (UN), having established strategies that aim to shift the focus of conventional generations to renewables ones. Such as Cape Verde, a number of countries are committed to meeting ambitious targets based on energy plan models that fundamentally propose the increase of renewable penetration, the improve of energy efficiency and the reduction of the emission of greenhouse gases [1].

With that paradigm shift, the grid faces new challenges related to the intermittent and stochastic nature of renewable energy sources, that represent the main challenge. This one consists in not compromising the grid stability, with frequency variations or voltage fluctuations, easily aroused by the variability of renewable generation. Thus, to make renewable energy as a reliable primary power source, it is necessary to solve the technical and practical problems caused by the intermittency and non controllable nature of its generation. The Energy Storage Systems (ESSs) are seen as being a crucial element in this paradigm shift helping the acomodation of the renewables and supporting in energy management and power quality applications. Within the ESSs, the Battery Energy Storage Systems (BESS) are one of the most mature storage technology and they can be use in a wide range of applications, as load levelling, non-spinning reserve, primary frequency control or bridging power. Among the various technologies of BESS, the lithium ion batteries are the ones that exhibit higher efficiency and energy density. The main hurdle of them imposition in the electrical storage systems, is the relatively high cost due to the need of his cells to have internal overcharge protection circuits, for safety reasons [2]. Although, the growth of its use in the market of electric vehicles, has contributed to improve the technical maturity of lithium-ion batteries and consequently to the cost decline of them in the recent years.

In this article as example of this, is studied the particular case of the Brava Island following the renewable energy plan of Cape Verde [3], developed by the energy consulting company GESTO Energy, in 2011. It is the smallest island of Cape Verde and presents interesting levels of solar and wind resources. Until 2020, it was established the goal of making the island generation system 100% renewable, with the implementation of a wind and a solar power plants. To support this, installing a BESS is also part of the plan goals being a crucial element in the aid of the integration of renewables. The battery is also necessary to improve the stability and flexibility of the grid once no synchronous generators are supposed to operate. Therefore, in this article it is performed the sizing of the BESS according to the needs of the grid and presented a feasibility study of the 100% renewable scenario analysing the stationary and dynamic behaviour of Brava electrical system.

So, in this work the main objective is to provide the results that allow find out what will be the impact of the BESS on the network and how is planned the operation of the electricity system for 2020, appraising the stability and feasibility of the renewable energy plan proposed.

A. Outline

This document is organized in five sections. This one makes an first introduction of the content of the work and are presented its main objectives. In Section II are exposed the essential contours of the case study, based on the renewable energy plan of Cape Verde [3] and in the necessary reformulations of it. It is approached the generation and distribution system planned to Brava island, in 2020, as well as it is described the BESS in more detail in a more theoretical point of view. Section III describes in a succinct manner the way the case study was implemented/modelled and the considerations to develop the simulations in PSS/E. Section IV makes the overview of the results obtained from the simulations studied for the power flow and dynamic behaviour of the system. Lastly, in Section V the essential conclusions about the work are drawn and the final considerations are made.

II. Case Study

Brava Island is the smallest island of Cape Verde archipelago, with approximately 7 thousand of inhabitants that live in an area of 67 km^2. The island is characterized by interesting levels of renewable resources, namely by presenting high solar expose and wind speeds exceeding 9 m/s, however it does not present potential of hydroelectric energy production.

The production and distribution of electricity on Brava island is guaranteed by ELECTRA. In 2015, the island still had no renewables facilities installed, so the electric production system was made by one thermal power station with 1770 kVA called Central Termoelectrica de Favetal (CEFV).

For 2020, the energy plan outlined in [3] for Brava Island was followed in the studies made in this work. This plan was made in 2011 by GESTO Energy and presents the demand forecast to 2020 for the island and exposes all the planned renewable projects to be installed until 2020, based on this projections.

In the next subsections are explored the main changes between the actual electricity system and the one projected to 2020. Are also presented the new projections made for the demand in 2020 based on most recent data, and consequently the re-dimensioning of the renewable projects that were planned in [3].

A. Load, wind and solar forecast to 2020

To sizing the BESS and to formulate realistic simulation scenarios for 2020, it was necessary to make the forecast of the load curve and of renewable resources (wind and irradiation).

The demand evolution prevision made in 2011 on [3], for 2015 and 2020 is predicted based on the historical and in the growth expected to the different sectors (tourism, domestic demand, etc) of the island. The load data of 2015 supplied by ELECTRA have proved that the demand forecast made in [3] was too ambitious. Given that, the load forecast for 2020 that was used in this work, was based on the load data of 2015, where a extrapolation of the data to 2020 has been applied based on the expected growth rate of demand between 2015 and 2020 presented in [3], that suppose an increase of 20.6% in demand compared to 2015. So, the load curve obtained can be observed in figure 1.

About the forecast of the renewable resources it was considered that either the profile of irradiation or wind the will remain nearly equal to the actual ones, so it is used the profiles data of 2015. With this is possible to estimate the total available power generated by the renewable power plants.

B. Generation and distribution systems

With the objective of decommissioning until 2020, the thermal power station of Brava island, that has 4 groups with a total installed power of 1,77 MVA, it was planned the installation of a solar farm (Parque Solar da Furna- PSF) and a wind farm (Parque Eólico Vento Furnas- PEVF). The projects presented in [3] were dimensioned according to the load forecast presented in it. With the new forecast made, it was considered appropriate to restructure the renewable projects to be installed in Brava island.

So, two DFIG wind turbines Vestas V29 with rated power of 225 kW each will compose the wind power plant, with an installed power of 450 kW. The solar power plant will integrate 1600 PV modules of 225 Wp what means an installed power of 360 kWp. The total available power generated by each of the renewable power plants is shown in figure 1.

Relatively to the MV distribution grid of the island, it operates at 2 different levels of voltage 6 kV and 20 kV, which feed 18 loads being the main one PT Vila. That corresponds to the main urban center of Brava island and represents about 30% of the total load of the island. The distribution grid has a radial configuration and it is composed by underground and overhead transmission lines.

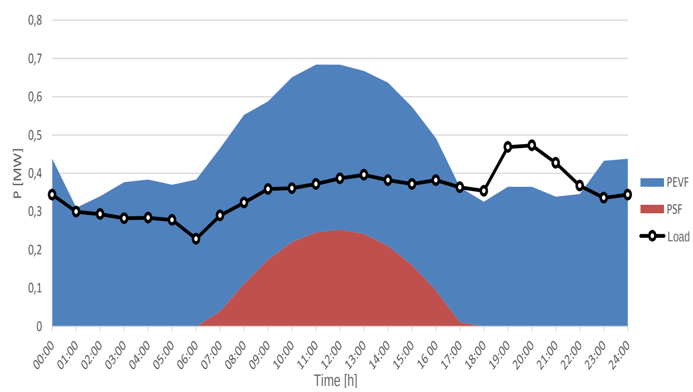

Fig. 1: Load curve and available power generated by the renewables facilities.

The figure 1 data is the base of all the simulations developed.

C. The BESS

With the implementation of the renewable energy projects identified in subsection II-B, it is intended to install an energy storage system that allows them to be integrated, in order to guarantee the island energy sustainability with a 100% renewable generation penetration. The storage system to be introduced is a secondary battery, namely a lithium-ion battery. The choice of this technology is motivated by the odd technical characteristics that it presents relatively to high efficiency and density of energy/power comparatively to the other BESS technologies. The cost of the BESS was not object of attention. The control and power condition system (C-PCS) is a fundamental part of the BESS, once it works as interface between the battery and the grid and allows the battery to adapt the working mode to different applications. The C-PCS it is normally composed by a converter, a temperature control system and management systems that control the battery operation. The Voltage Source Converter (VSC) is the natural choice for the bi-directional converter, once it allows independent control of active and reactive power. Therefore, with an convenient control strategy the BESS is able to control fast the exchange of reactive and active power in both directions.

The battery to be installed would be used either in energy and power applications, hence, the scaling of the BESS was done considering that. Despite this, for a 100% renewable generation system the main objective of the BESS are the energy applications, as non-spinning reserve or load leveling. This means that its central purpose is associated with the operating cost of the electrical system, helping to improve the profitability of it enabling the increase of renewable penetration. Hence, what is desirable is that the BESS could store the excessive produced power in relation to the load to later use it when more suitable, allowing the time shifting of energy. However, the BESS should also contribute to voltage and frequency regulation in order to maintain network stability. The fast response of the battery make it suitable to deal with the wind intermittency smoothing the power output and thus contributing to the power quality or to respond promptly to any contingency with injection/absorption of power.

III. Implementation

All the studies were made using the PSS/E software developed by Siemens. All the elements of the network were modelled using the PSS/E libraries models, namely the BESS is modelled by ”CBEST” and ”PAUX1” whose detailed information can be obtained in the manual [4]. The ”CBEST” model represents the battery model and it is composed by one active power path and an reactive power path models. The active power path simulates the active power that is exchanged by the BESS during a simulation. It has in consideration the power inefficiencies of the battery in th storage and retrieval of energy and also the limitation of AC current defined for the converter. This model requires one external input that indicates the function that the battery perform. This external input is provided by the auxiliary model ”PAUX1”. ”PAUX1” is a frequency sensitive model that impose a power output according the deviation of frequency from nominal. It is basically composed by a proportional controller, an associated gain (K_C) and time constants. So, the model receives as input signal the frequency deviation, in p.u, for the bus where the BESS is connected and generates a output power, in MW, that is proportional to the gain K_C, in MW/p.u.. Then, that output power is connected to the input of the ”CBEST” model. About the reactive power path, it is comprised by a voltage regulator model that has a similar behaviour that the STATCON model. The regulator is responsible for controlling the reactive current part , instead of the internal voltage. The model was designed to give priority to the active power so the limits of current imposed by the model are the couterpart of the current limits defined in the active power path [5].

About the sizing of the BESS, it was made following the next steps:

1) Calculate power surplus/deficit, $P_{dif}(t)$, between the available renewable power, $P_{ren_{disp}}(t)$, and the load power, $P_{load}(t)$, for each hour showed in figure 1. So,

$$P_{dif}(t) = P_{ren_{disp}}(t) - P_{load}(t) \; . \tag{1}$$

2) Calculate the average energy required for the battery, E_{bat}. Thus,

$$E_{bat} = \sum_{j=1}^{24} P_{dif}(t) \times \Delta t \; , \tag{2}$$

where Δt represent the dispatch period and it was assumed equals to 1 hour;

3) Calculate the real capacity needed for the battery operation, E_{bat_N}. This approach takes into account the influence of depth of discharge (DoD %), autonomy (Aut) and battery aging (Fc %). Therefore,

$$E_{bat_N} = \frac{Fc \times E_{bat} \times Aut}{DoD} \; , \tag{3}$$

where $Aut = 1\ day$, $DoD = 85\ \%$ and $Fc = 110\ \%$;

4) Choose the nominal power P_n of the BESS based on the reactive power required in the worst case, assuming a power factor of 0,9 to the BESS.
5) Calculate the number of cells in parallel and series that the battery must have to achieve the capacity and voltage defined to the BESS, respectively.
   a) Modules in series: Each module is composed by 4 cells in series with 3.2 V each. So, to reach the BESS operation voltage, V_{out}, 32 modules in series are required.
   b) Modules in parallel: The quotient between the nominal capacity of the E_{bat_N} battery and the individual capacity of each cell module (3.6 kWh) gives the number of modules to be connected in parallel to reach the nominal capacity defined for the battery. So, are needed 29 modules in parallel.

In table I are shown the technical features of the BESS to be implemented in the study case, that was calculated based on the above steps and in the data exposed on figure 1.

TABLE I: BESS technical specifications.

P_n [MW]	0.875
E_{bat_N} [MWh]	3.5
V_{out} [V]	400
Discharge/charge time [h]	4
DOD [%]	85
E_{bat} [MWh]	2.7
Nº modules in series	32
Nº modules in parellel	29

A simplified planning of a possible dispatch of the electro-production system with the battery and the renewables was executed respecting the following:

- Assumptions:
  - The BESS should be kept in service 24 hours a day;
  - The last unit to be dispatched and which is responsible for meeting network losses is the battery;
  - Negative power corresponds to BESS charging. Graphically it was represented as the area over the demand curve;
  - The state-of-charge (SoC) has to do a daily cycle, by presumption.
- BESS technical restrictions:
  - The power at which the battery is charged/discharged should respect the balance between generation, P_{ger}, and demand, P_{load}. So, the power of BESS the power at which the battery is dispatched, P_{BESS}, is given by:

$$P_{BESS}(t) = -(P_{ger}(t) - P_{load}(t)) \tag{4}$$

  - BESS power limits should be respected. So, $-0.875MW < P_{BESS}(t) < 0.875MW$;
  - The capacity limits of the battery must be taken into account, so that they are not exceeded and not compromise the safety and lifetime of the BESS. Thus, the energy of the BESS, E_{BESS}, should respect the limits of operation. So, $15\%E_{bat_N} < E_{BESS}(t) < E_{bat_N}$. The $E_{BESS}(t)$ is calculated by:

$$E_{BESS}(t) = E_{BESS}(t-1) + \Delta t \times P_{BESS}(t) \ . \tag{5}$$

  - The SoC limits should be respected too. The SoC is defined by:

$$SoC(t) = SoC(t-1) - \frac{E_{BESS}(t)}{E_{bat}} \ , \tag{6}$$

    as it is consider the total capacity of the BESS, E_{bat_N}, the SoC is referred to that, so it should be maintained between $15 < SoC(t) < 100\%$.

The figure 2 shows the dispatch of the units of generation of Brava Island in the 100% renewable panorama.

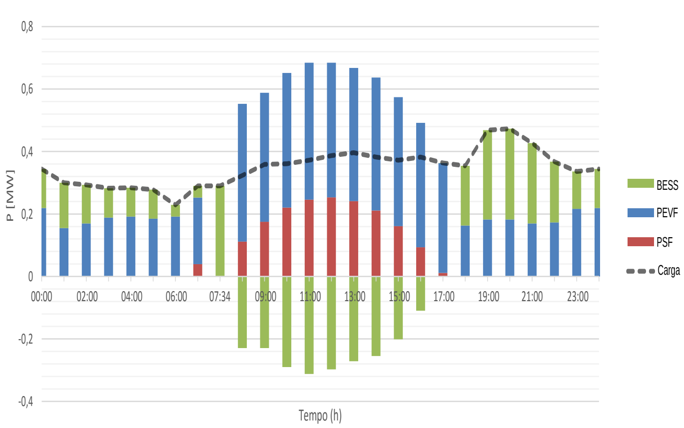

Fig. 2: Generation units dispatch for the 100% renewable panorama.

The SoC of the BESS relative to the dispatch of figure 2, is exposed in figure 3. It is important to reinforce the fact that in this figure the percentages of SOC's are relative to E_{bat}.

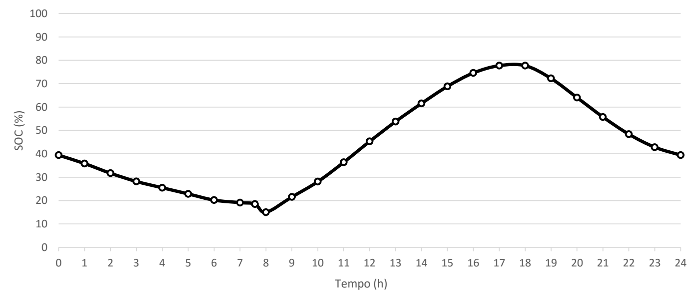

Fig. 3: BESS SoC for the 100% renewable panorama.

In order to develop the stationary and dynamic simulations in PSS/E were selected four simulation scenarios (I to IV) that were studied. Each of them characterizes a different load/generation scenario:

- The scenario I corresponds to the off-peak period (6:00);
- The scenario II corresponds to the moment when the available renewable generation is maximum (11:00);
- The scenario III corresponds to a intermediate scenario (16:00);
- The scenario IV corresponds to peak period (20:00).

IV. Simulations

In this section are presented the studies carried out with the aim of exploring how the Brava island network will govern a 100% renewable panorama, either from the point of view of power flow or transient stability.

A. Power Flow

The results obtained from the simulations in steady state are presented for each of the scenarios introduced, in table II.

TABLE II: Power flow results for Brava 100% renewable system.

Scenarios				I	II	III	IV
Load			P (MW)	0,229	0,372	0,382	0,473
			Q (Mvar)	0,172	0,279	0,287	0,355
Renewable Generation	PSF		P (MW)	0,000	0,246	0,094	0,000
			Q (Mvar)	0,000	0,081	0,031	0,000
	PEVF	AG1	P (MW)	0,192	0,219	0,199	0,183
			Q (Mvar)	0,048	0,047	0,040	0,015
		AG2	P (MW)	0,000	0,219	0,199	0,000
			Q (Mvar)	0,000	0,047	0,040	0,000
BESS			P (MW)	0,038	-0,310	-0,108	0,293
			Q (Mvar)	0,134	0,144	0,201	0,368
Losses			P (kW)	0,50	1,91	1,70	2,60
			Q (kvar)	9,63	39,66	24,42	28,10

The analysis of the results of the power flow look over voltages, losses, overloads and production in the grid. Firstly, a problem of overload emerged with the increase of the demand to 2020. For the scenario IV, the peak power lead to that, a transformer became overloaded in the SS Nova Sintra. The proposed solution suggests the introduction in parallel of an equivalent transformer. Relatively to the bus voltages, all of them operates within the limits assumed as acceptable ($\pm 5\%$

of the nominal voltage). The losses presented in table II reveal that the reactive power losses are the most relevant, representing on average about 8% of the reactive power injected. Lastly, with the dispatch defined it is verified that 2.709 MWh of renewable energy is wasted, which represents around 24% of wasted energy compared with the total available renewable energy (11.136 MWh).

From the table II it is possible to verify that the BESS assumes a determinant role in the generation of reactive power, since it was defined that all the renewable facilities operates with a power factor equals to 0.95.

B. Dynamic Simulation

The dynamic simulations are aimed for evaluating how the Brava island's grid behaves towards a certain contingency that affects the operation of the network and its steady state. With all the simulations done, the objective is to reach the necessary conclusions about the stability of the system when it is explored only by renewables and supported by a energy storage system. Therefore, were performed 3 different disturbances:

1) Short circuit during $100ms$, on an electrically centric bus;
2) Irradiance variation;
3) BESS out-of-service.

The operating conditions to qualify the steady state that is reached after the disturbance are, for:

- Frequency - the system can operate safely if in steady state the frequency deviation does not exceed $\pm 1,5Hz$. So, the network must operate within the range of $48,5 - 51,5Hz$.
- Voltage - the system can operate safely if in steady state the voltage of any bus does not exceed $\pm 10\%$ of the rated voltage. So, the permissible voltage levels are within the range of $0,9 - 1,1p.u.$.

In the first simulation, the main objective is verify how the grid reacts when a short circuit occurs. The perturbation applied was a three-phase symmetric short-circuit characterized by a susceptance of $-2 \times 10^9 p.u.$, at BUS50-VILA that is an an electrically centric bus.

It was verified that the short circuit makes the PV's voltage relays to actuate disconnecting them from the grid. This fact, causes the loss of generation and consequently the drop of the frequency. For the worst scenario (II), the one where the solar penetration was bigger, the frequency stabilizes at $48,8Hz$ in the steady state. All the voltages remain within the limits and there were no overloads in either branches or machines.

For the second simulation, the main purpose was to test the impact of the variability of renewable resources on the stability of the grid. So, the simulation performed consists in varying the irradiance admitting the occurrence of cloudiness, which is reflected in a fast decrease of the irradiance incident on the PVs panels and consequently in the power produced by them. The scenario II is the one where the solar penetration is highest, so it was used to study this perturbation.

In the figure 4 is presented the response of the PEVF, and in figure 5 is exposed the response of the BESS, PV's and the frequency of the grid.

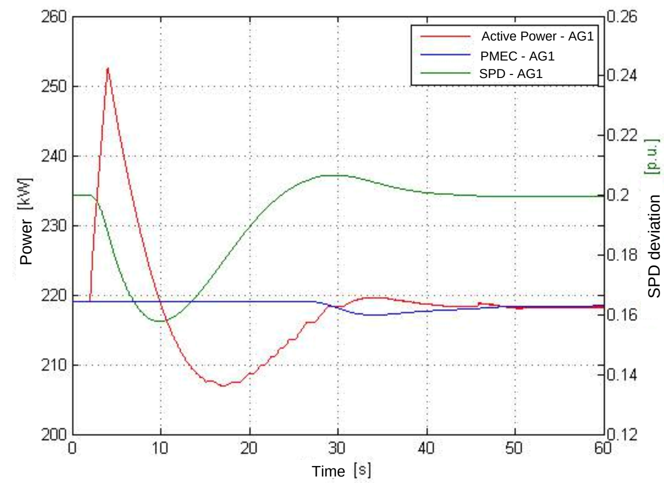

Fig. 4: Response of one wind turbine (AG1) from PEVF, to the irradiance variation.

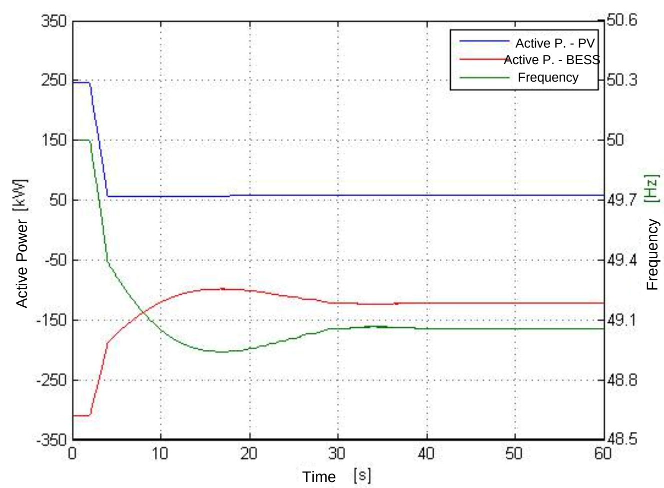

Fig. 5: Response of the PV's from PSF, of the BESS and grid frequency, to the irradiance variation.

In addition to the PV's, the two turbines of the PEVF and the battery (operating in charging mode) are in service in this scenario. For the results presented in figure 4, only one of the wind turbines is exhibited, since both have an equal dynamic response. In the figure 4 it is possible to verify the inertial response of the wind turbines. It is observed that the turbine increases the electrical power that they inject during the first moments after perturbation. As consequence, the rotor speed decreases or which means by another perspective the loss of turbines kinetic energy. In this way, these contribute to support the fast frequency deviation, resulting from the loss of solar generation. After the inertial response, the wind turbines decrease their generation in order to restore the speed of rotation. As it is visible from the $10s$, the electrical power is lower than the mechanical power, so the rotor begins to accelerate, what is translated in the increase of the speed deviation of the wind turbine. The mechanical and electrical power, in the steady state reached after the perturbation, presented values slightly inferior to those at which the turbines was being explored after the perturbation occurs. The speed stabilizes, at $50s$ of simulation, slightly below of $0.2p.u.$, moment when the balance between the mechanical and electrical torque is achieved.

In figure 5, it is possible to observe the behavior of the battery, during the simulation period. As already mentioned, the power at which the battery is charged/discharged is proportional to the frequency variation of the network. The final frequency deviation, that is reached after the primary frequency control operation occurs, is defined as a function of the gain K_C of the BESS model. As the primary frequency control system of the BESS is a proportional type, the frequency stabilization occurs at a lower value of the nominal (50 Hz), as verified. With the loss of solar generation, the battery responds by charging at a lower power, which is analogous to the decrease in network load, since the battery being charged is viewed by the network as a charge. In the steady state reached after the perturbation, the BESS operates at $-120,86kW$.

It was verified that this irradiance variation was well supported by the grid since no large fluctuations of voltage or frequency were observed. The system reaches to a steady state with a frequency of 49,05 Hz, as it is visible in figure 5.

The last simulation studies a contingency that impose the disconnection of the battery from service. The results obtained proves what has expected, that the grid is unable to be supported only by the renewables and that the system ends up collapsing shortly after the battery runs out-of-service.

V. Conclusions

The main objective of this work was to study the technical feasibility of implementing in Brava island a 100% renewable generation system supported by a BESS, following the renewable energy plan of Cape Verde for 2020 [3]. With the reformulated demand forecast and the adjusted renewable facilities projects, it was made simulations on steady and dynamic state.

From the analysis of the power flow results it was possible to conclude that the actual MV distribution grid is not prepared to the expected peak demand, originating overcharges in a particular zone of the grid (SS Nova Sintra) that could be solved with branches in parallel (e.g. transformers) as it was suggested. The renewable power that is lost, in the dispatch made, corresponds only to 24% of the total available power, which confirms an appropriate sizing of the renewable projects and BESS against the expected load. In addition, it was proved that the BESS has a key role in the production of reactive power and also in the integration of renewables in the grid.

The importance of the inertial control provided by the DFIG's and of the primary frequency control supported by the BESS is evident in the results obtained for the two first contingencies studied. It is its action that allows, that after each of the disturbances, the network reaches to a stable operating point. With the last simulation (BESS out-of-service) has been proved that the system is not capable of working without the battery, because no other facilities has the capacity to respond to the fluctuations of frequency and voltage of the grid. Therefore, complementary studies (presented only in the thesis) were carried out in which the smaller of the thermal groups of the island is considered in the dispatch, and with that, is lost some renewable penetration but is gained flexibility to survive in transient phenomenas.

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